US009411172B2

(12) **United States Patent**
Haddock et al.

(10) **Patent No.: US 9,411,172 B2**
(45) **Date of Patent: Aug. 9, 2016**

(54) **MULTIFOCAL LENS WITH A DIFFRACTIVE OPTICAL POWER REGION**

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(73) Assignee: **Mitsui Chemicals, Inc.**, Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 494 days.

(21) Appl. No.: **13/656,943**

(22) Filed: **Oct. 22, 2012**

(65) **Prior Publication Data**

US 2013/0114128 A1 May 9, 2013

Related U.S. Application Data

(62) Division of application No. 12/166,526, filed on Jul. 2, 2008, now Pat. No. 8,317,321.

(60) Provisional application No. 61/039,079, filed on Mar. 24, 2008, provisional application No. 61/039,081,

(Continued)

(51) **Int. Cl.**

G02C 7/02	(2006.01)
G02C 7/06	(2006.01)
G02B 5/18	(2006.01)
G02C 7/08	(2006.01)

(52) **U.S. Cl.**

CPC ***G02C 7/06*** (2013.01); ***G02B 5/1895*** (2013.01); ***G02C 7/061*** (2013.01); ***G02C 7/083*** (2013.01); *G02C 2202/20* (2013.01)

(58) **Field of Classification Search**

CPC G02C 7/047; G02C 7/04
USPC 351/159.11, 159.01, 159.12, 159.15, 351/159.35, 159.44, 159.75
See application file for complete search history.

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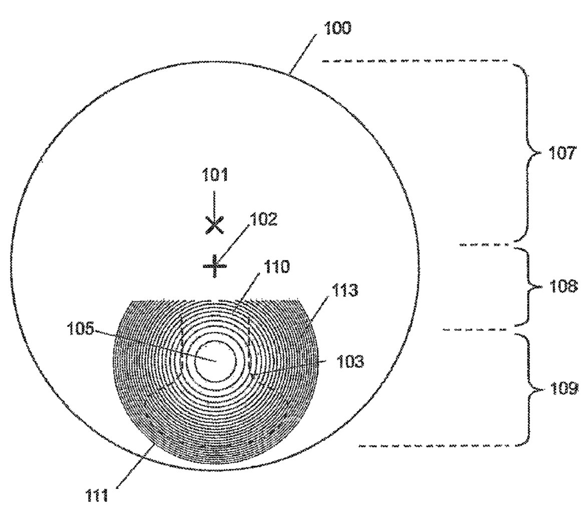
(57) **ABSTRACT**

A lens system is presented having a diffractive optical power region. The diffractive optical power region has a plurality of concentric surface relief diffractive structures. A greater portion of light incident on a diffractive structure near the center point contributes to the optical power than light incident on a diffractive structure peripherally spaced therefrom.

34 Claims, 33 Drawing Sheets



Related U.S. Application Data

filed on Mar. 24, 2008, provisional application No. 60/991,899, filed on Dec. 3, 2007, provisional application No. 60/987,556, filed on Nov. 13, 2007, provisional application No. 60/982,182, filed on Oct. 24, 2007, provisional application No. 60/929,570, filed on Jul. 3, 2007.

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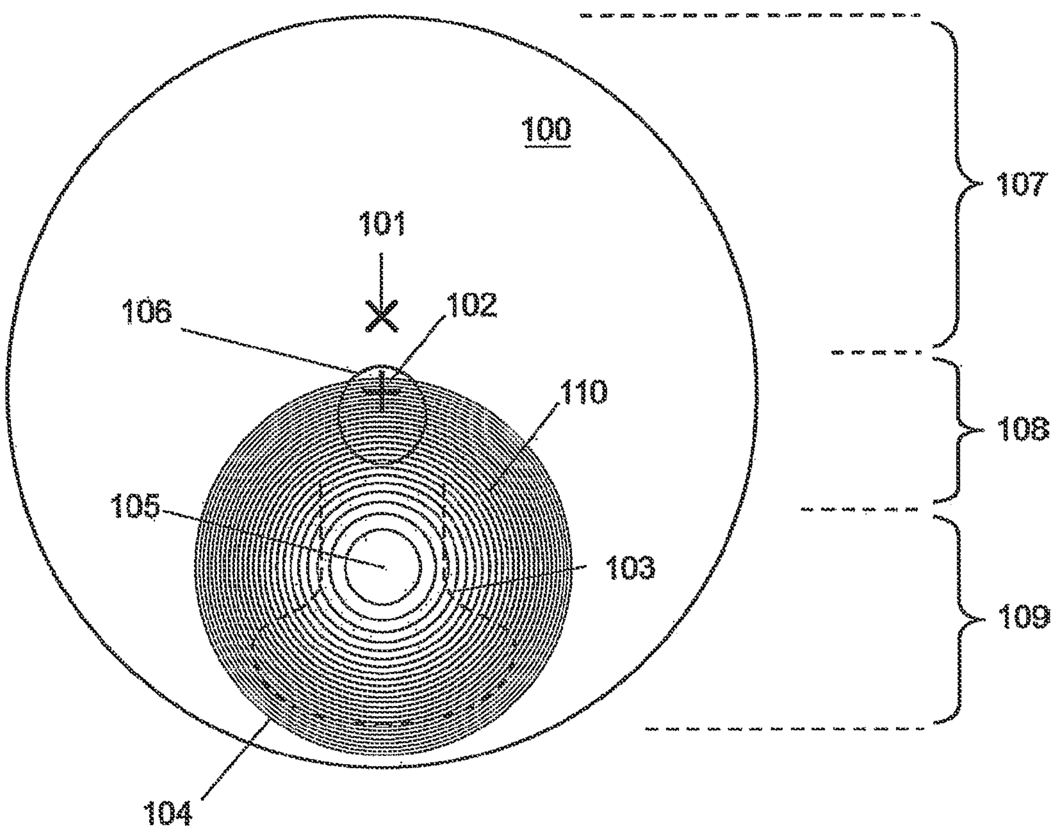


FIG. 1
PRIOR ART

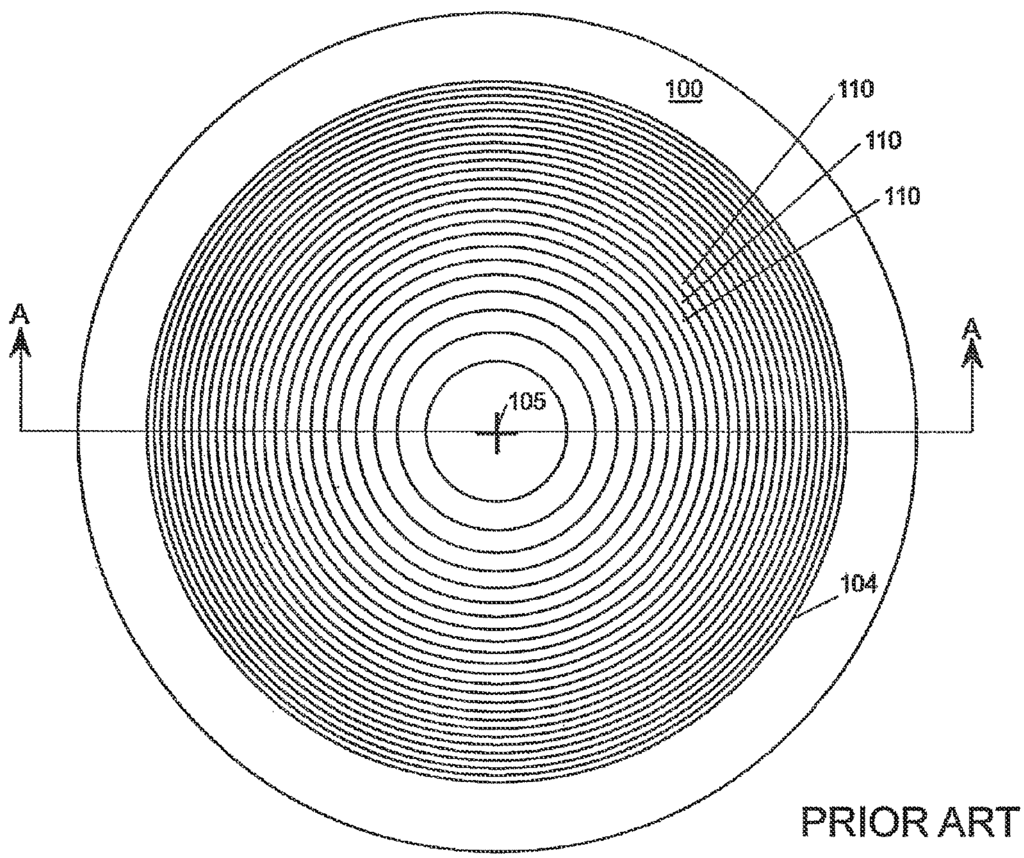


FIG. 2A

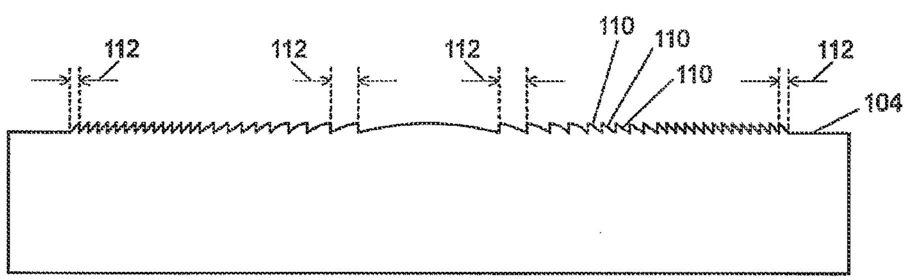
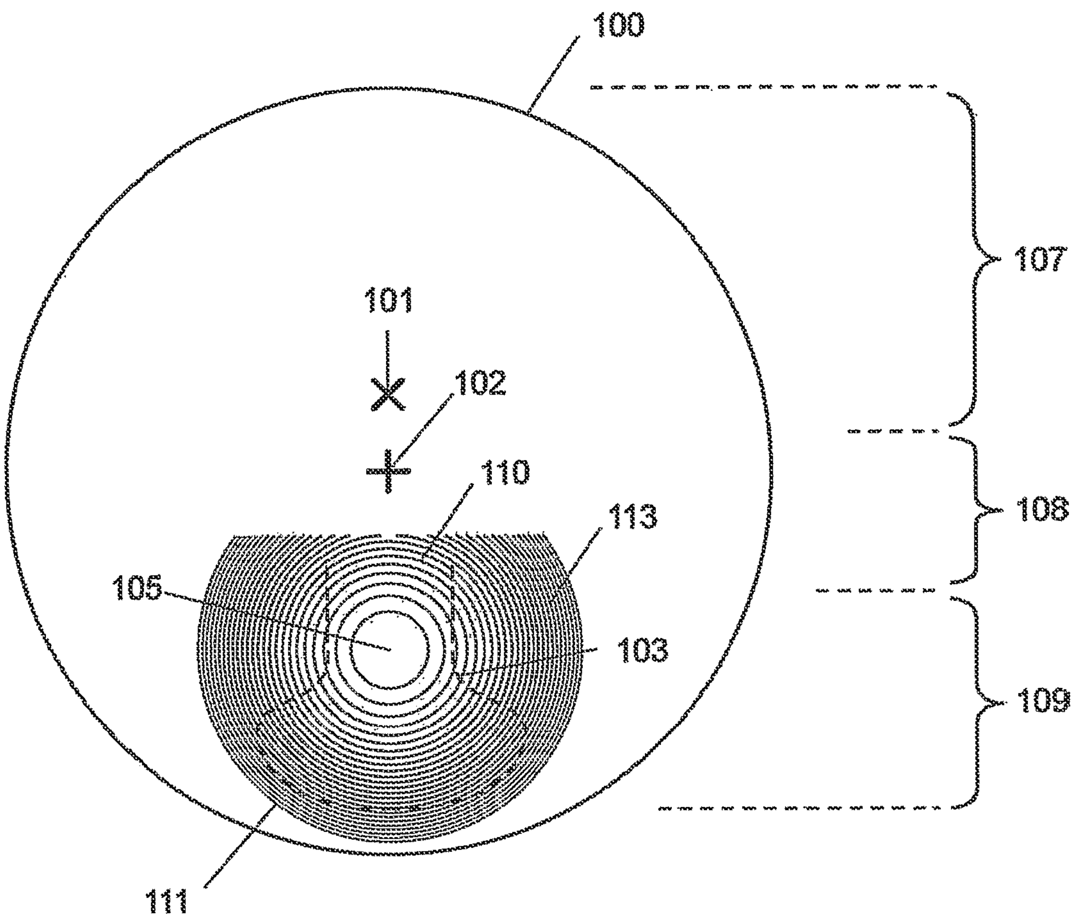


FIG. 2B

PRIOR ART



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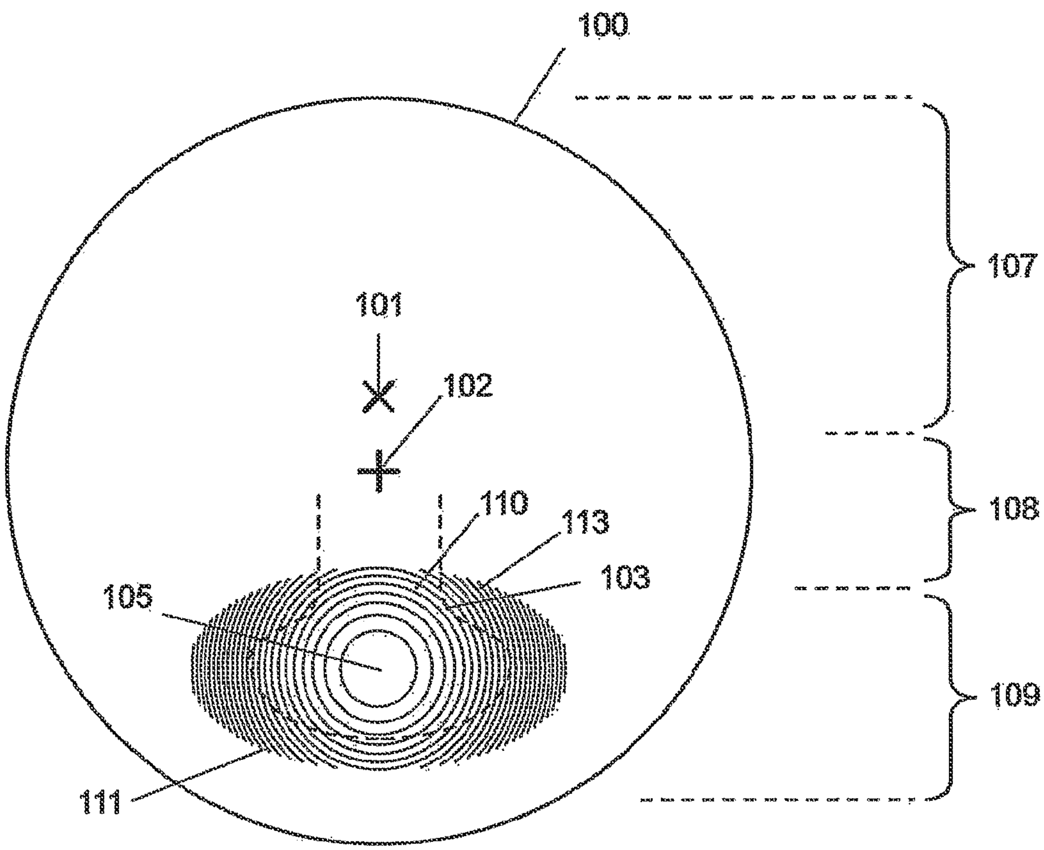

FIG. 4

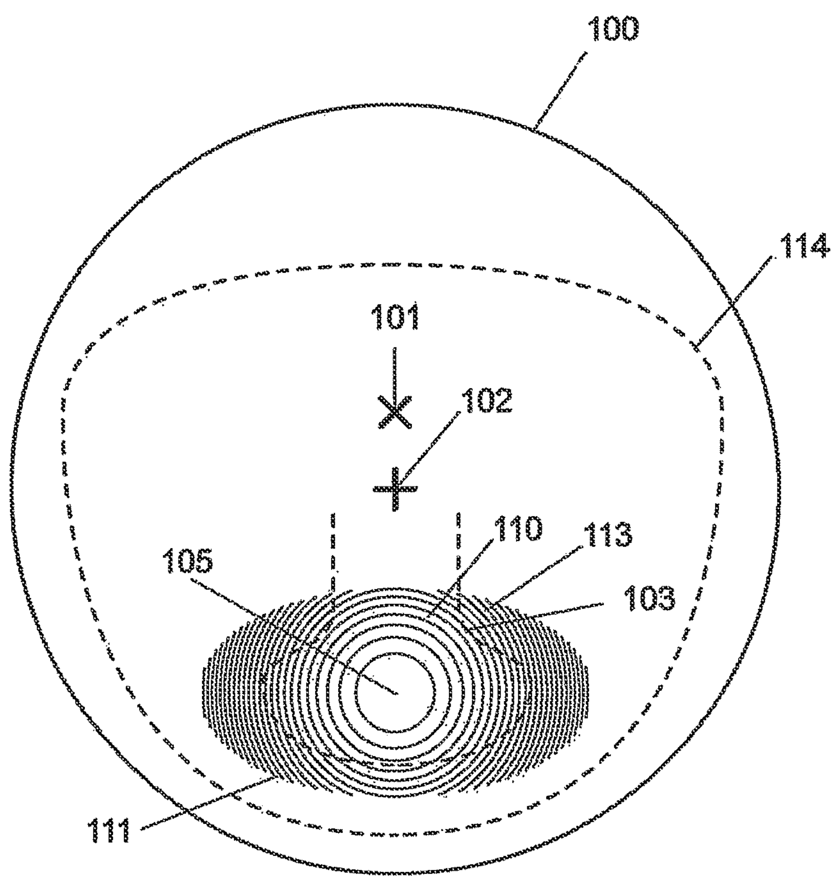

FIG. 5

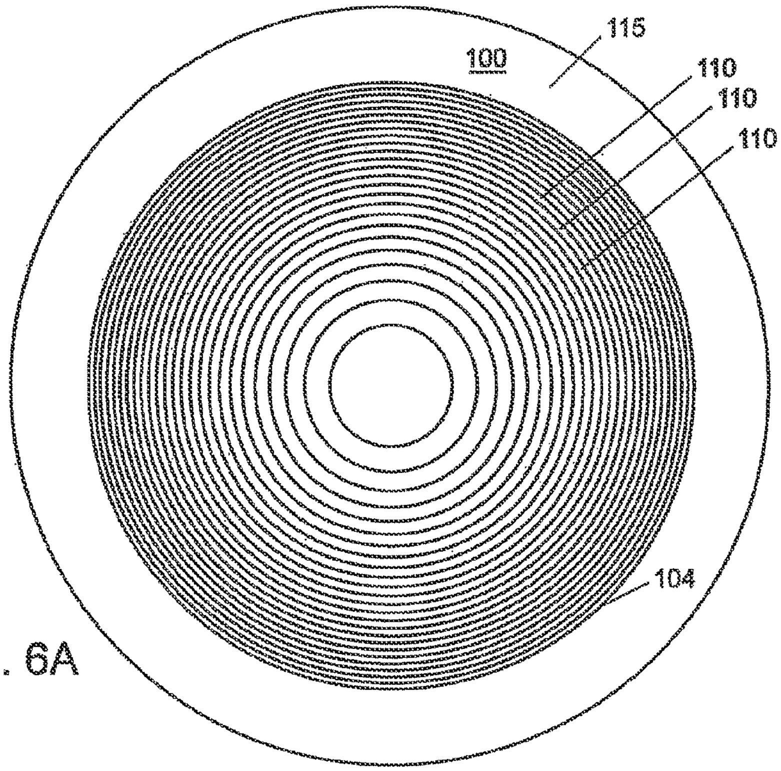

FIG. 6A

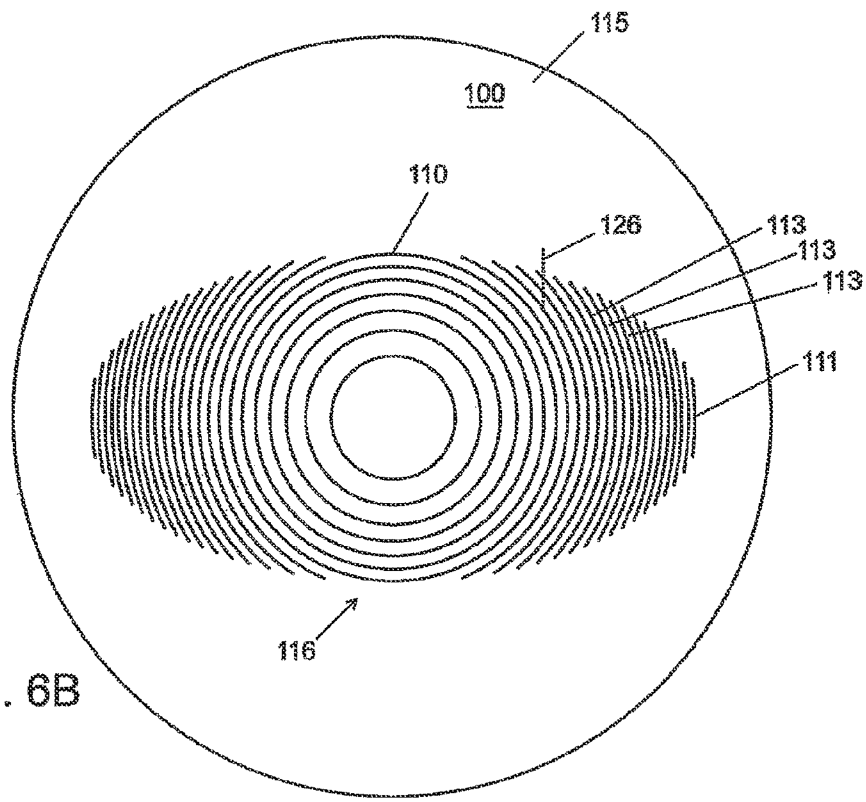

FIG. 6B

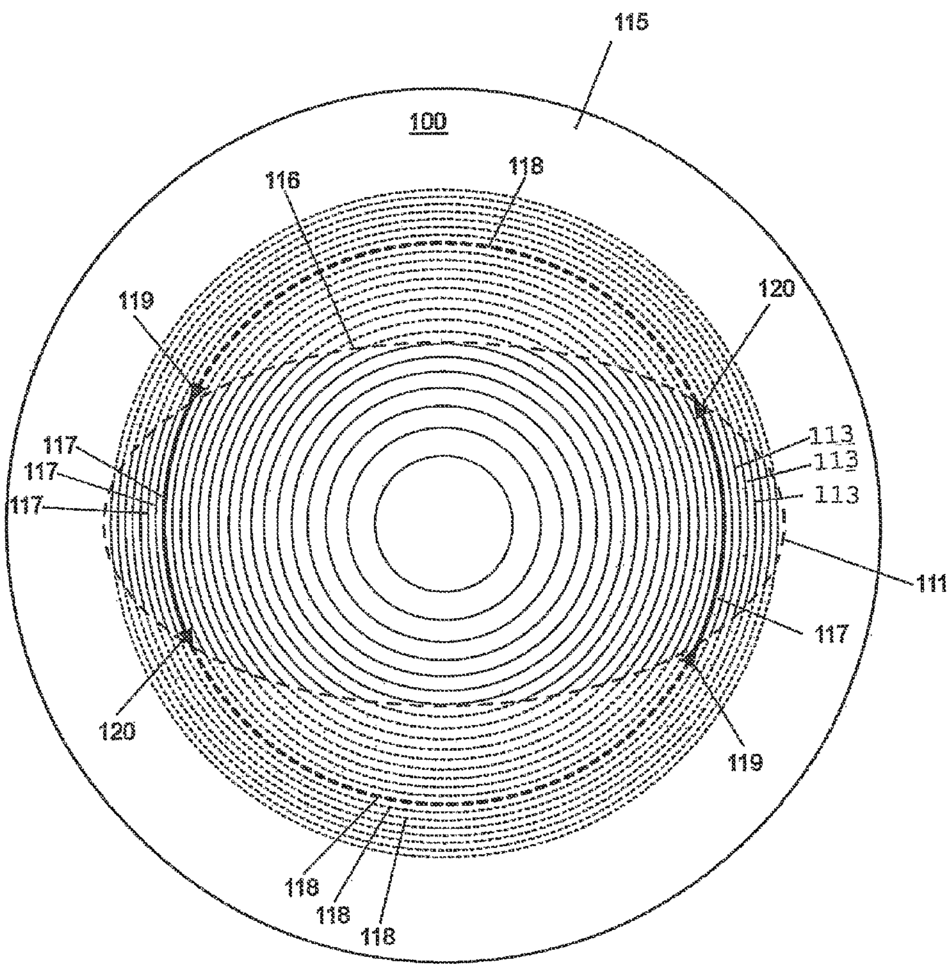
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FIG. 7

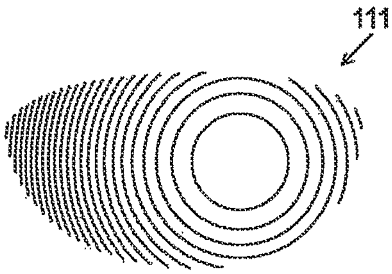


FIG. 8A

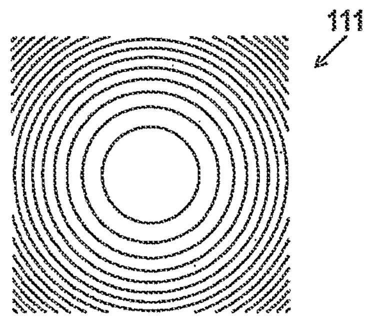


FIG. 8B

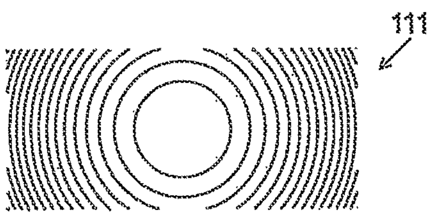
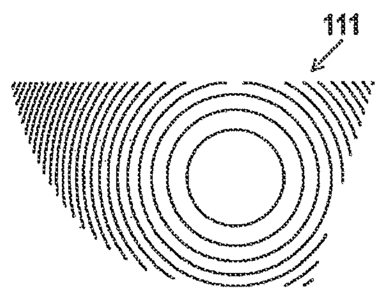


FIG. 8C



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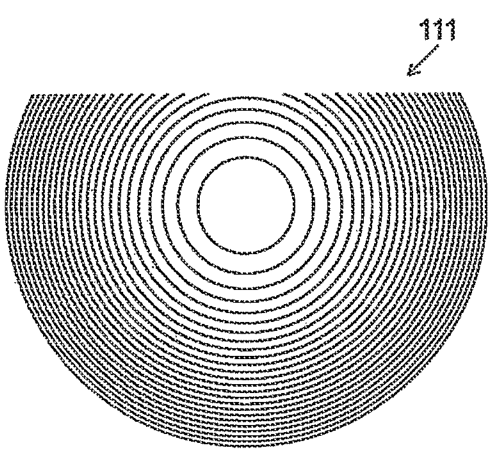

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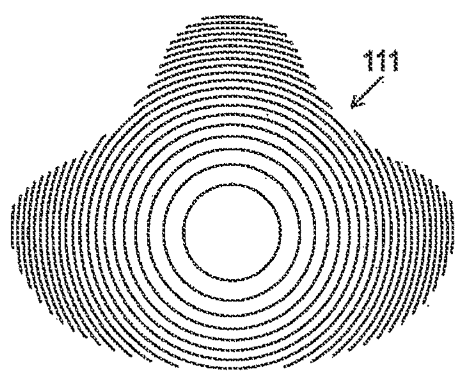

FIG. 8F

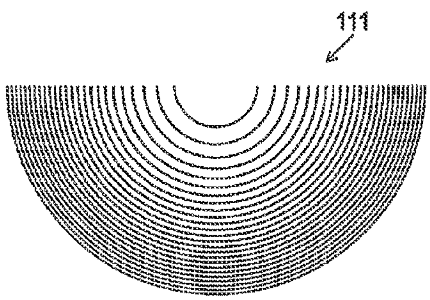

FIG. 8G

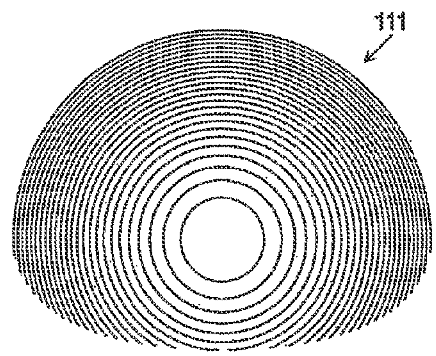

FIG. 8H

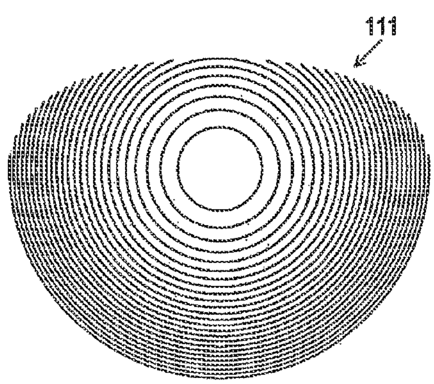

FIG. 8I

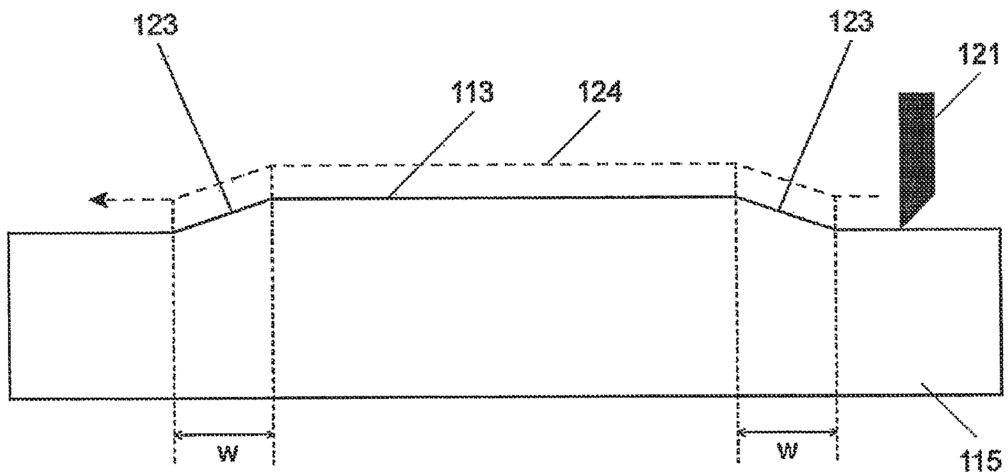

FIG. 9A

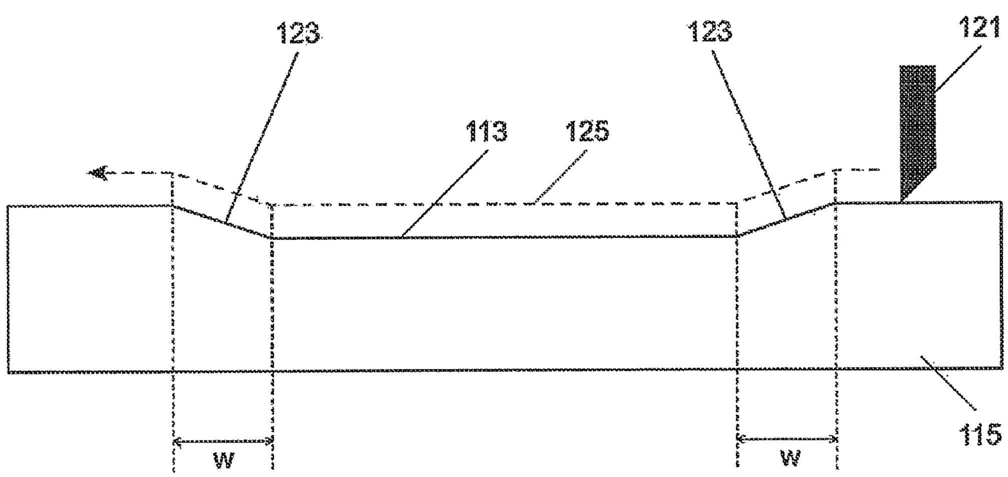

FIG. 9B

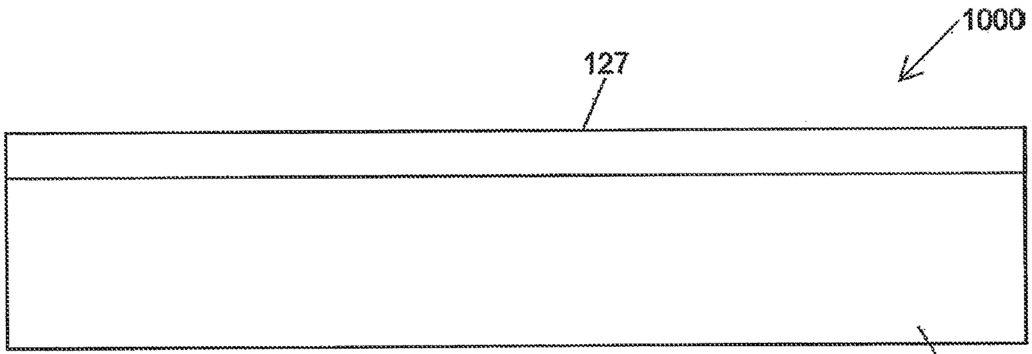

FIG. 10A

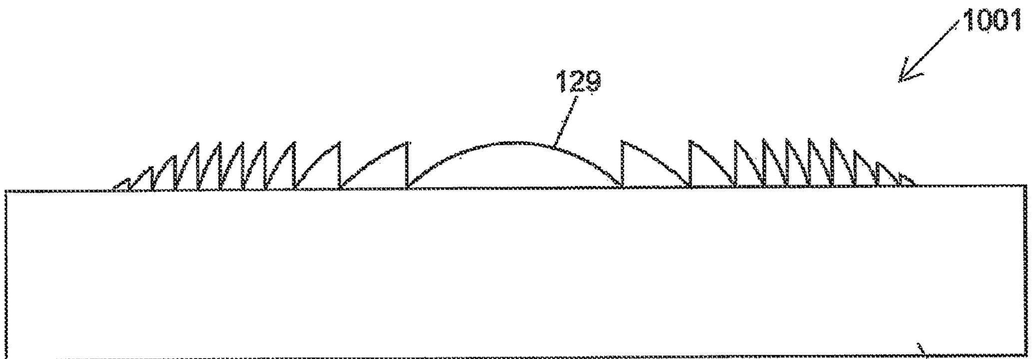

FIG. 10B

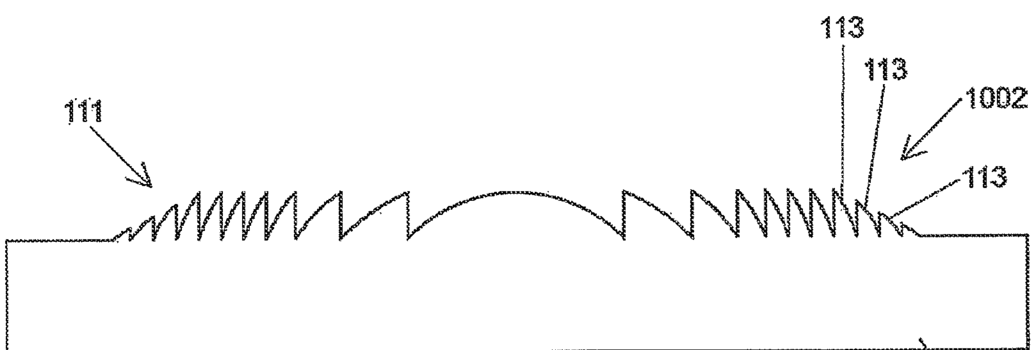

FIG. 10C

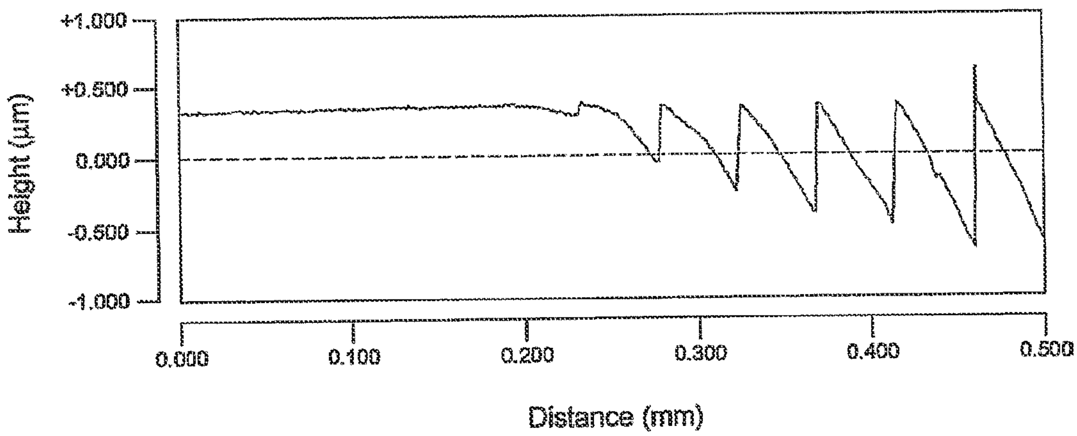
+1.000
+0.500
0.000
-0.500
-1.000
Height (µm)
0.000
0.100
0.200
0.300
0.400
0.500
Distance (mm)

Fig. 11

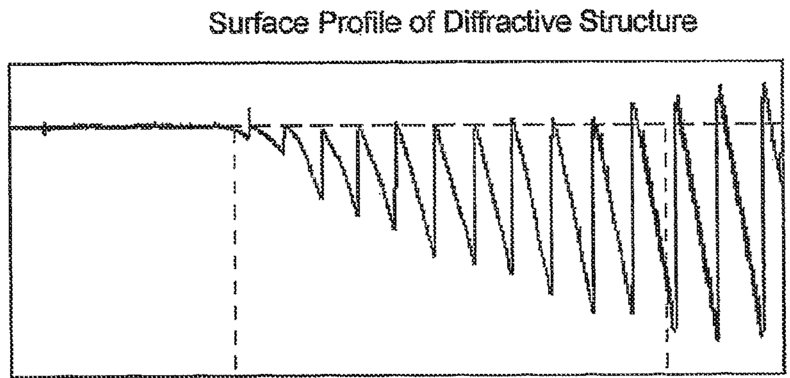

FIG. 12A

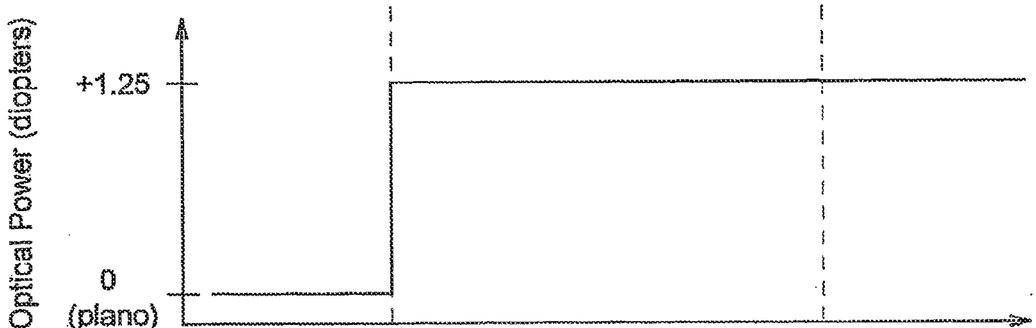

FIG. 12B

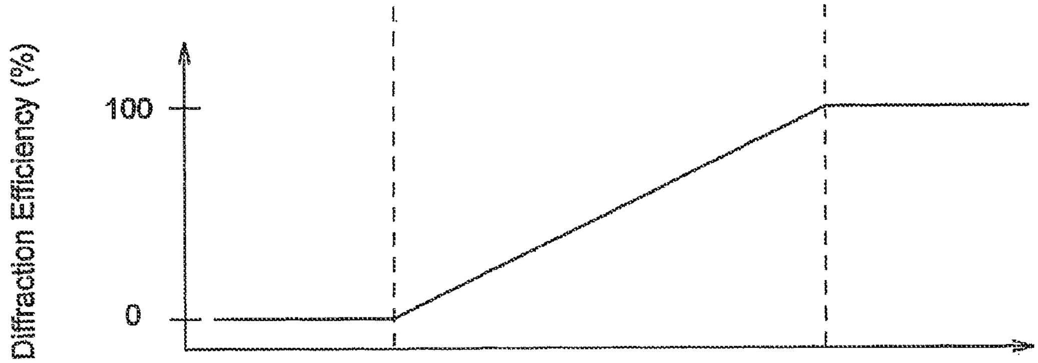

FIG. 12C

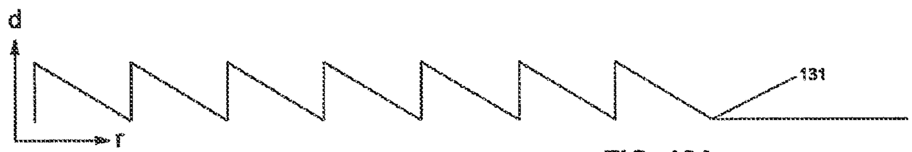

FIG. 13A

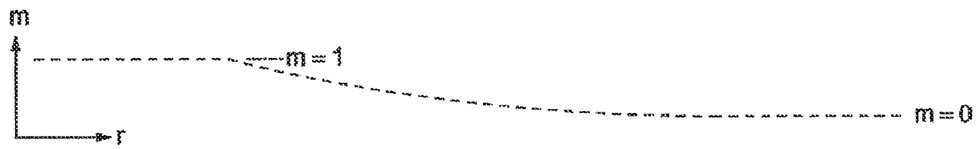

FIG. 13B

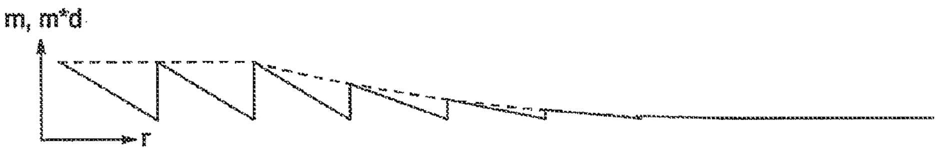

FIG. 13C

FIG. 13D

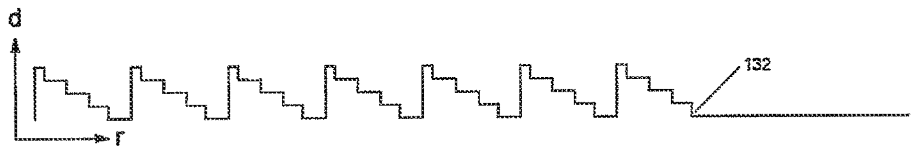

FIG. 14A

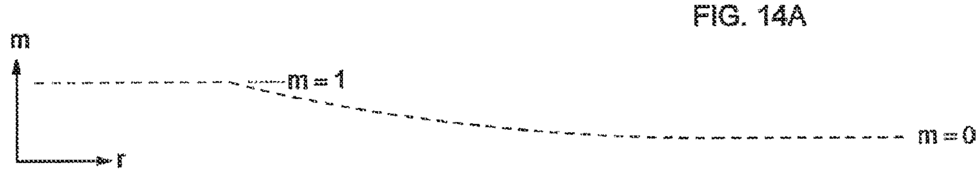

FIG. 14B

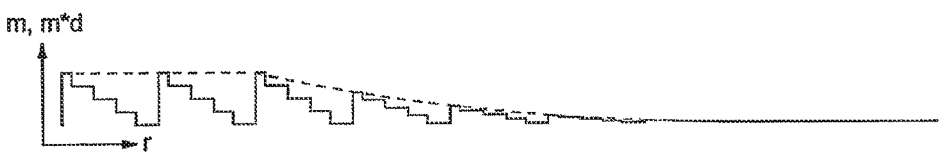

FIG. 14C

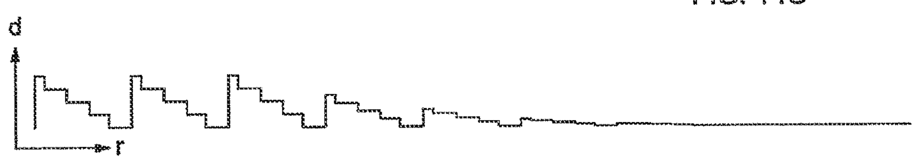

FIG. 14D

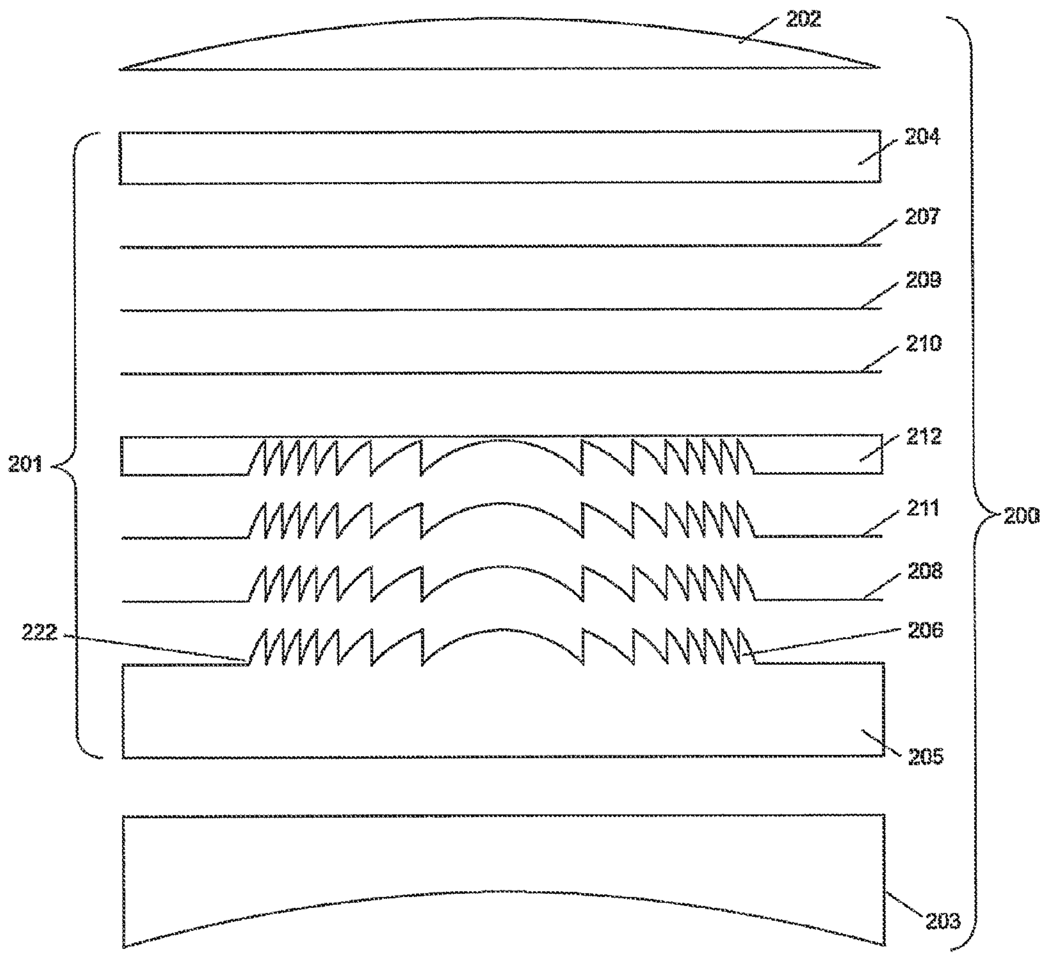

FIG. 15

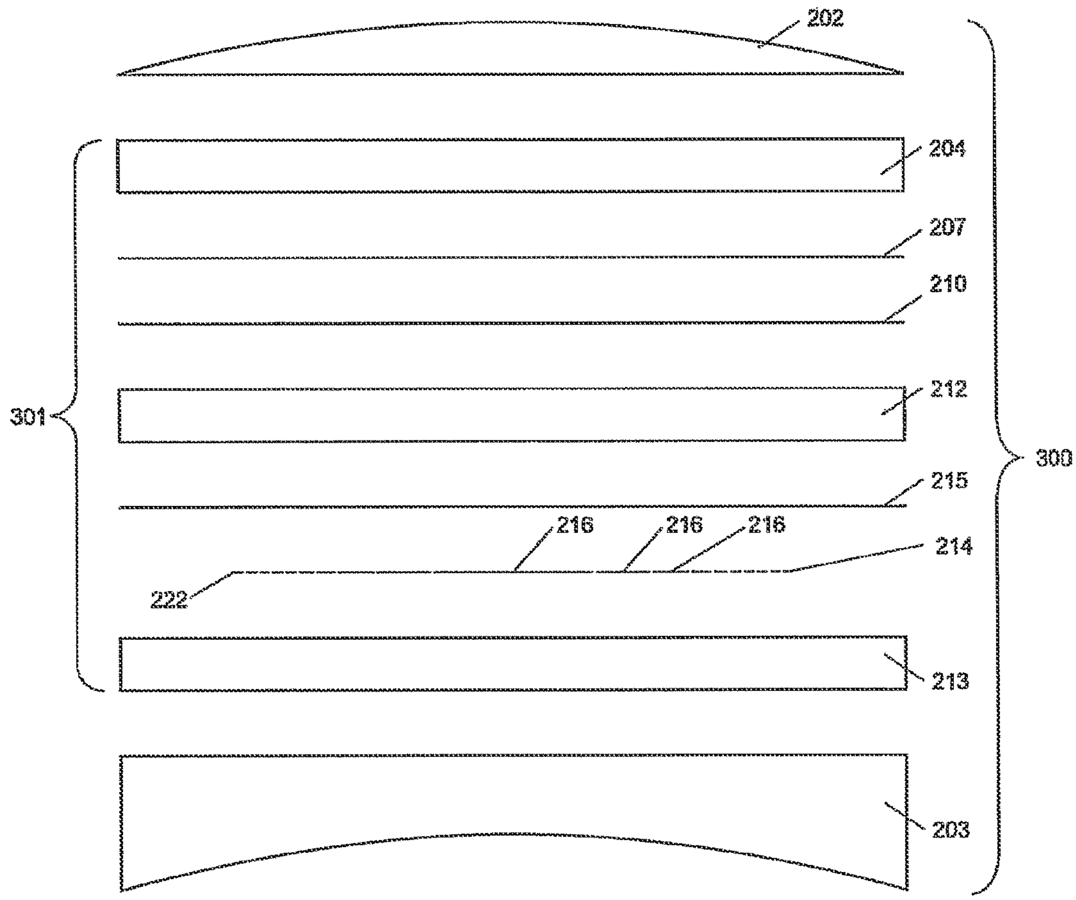

FIG. 16

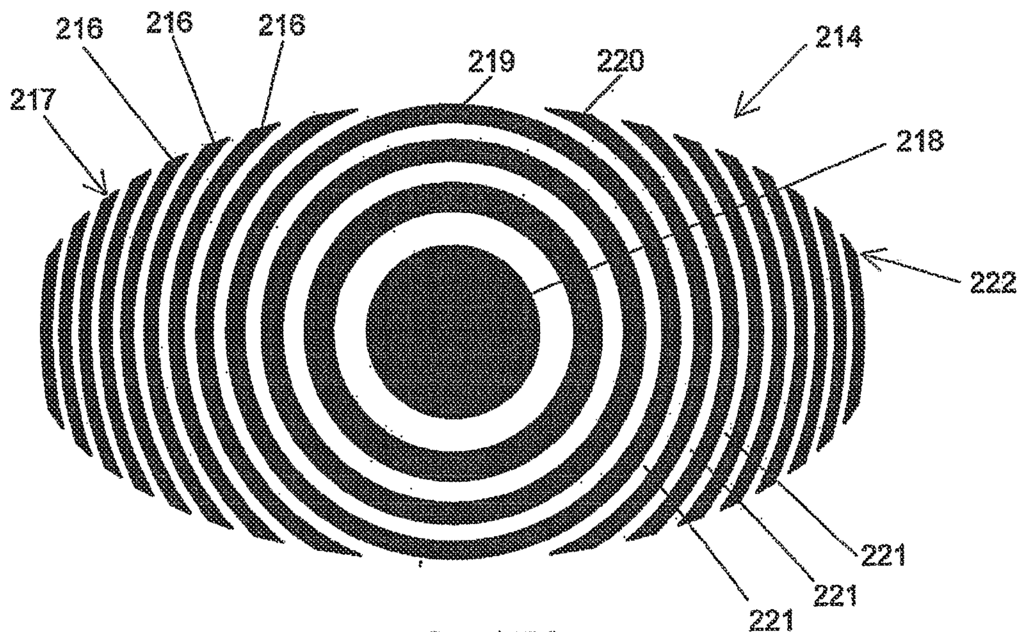

FIG. 17A

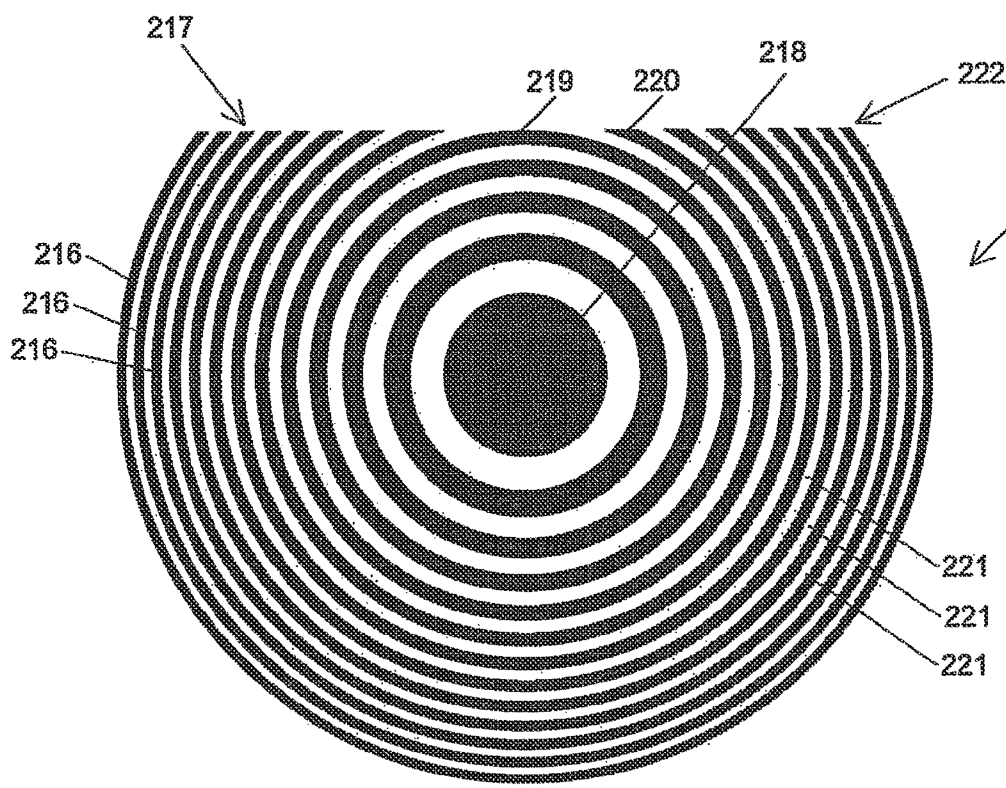

FIG. 17B

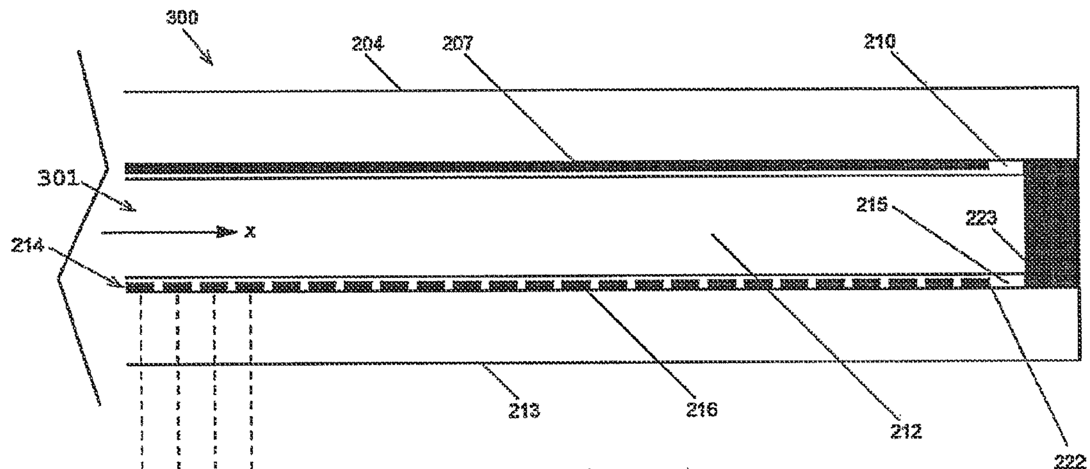

FIG. 18A

FIG. 18B

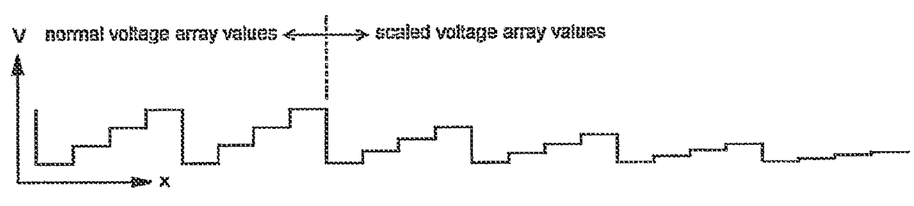

FIG. 18C

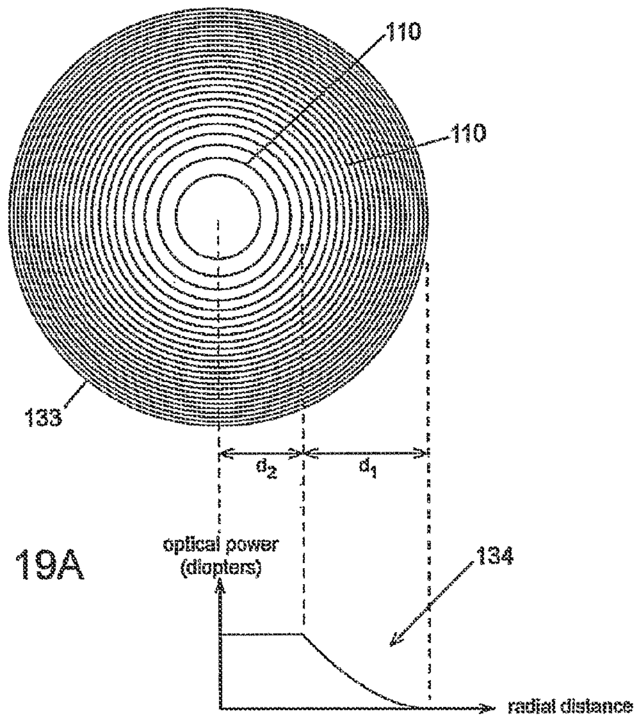

FIG. 19A

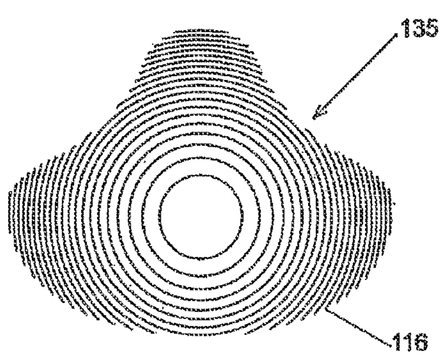

FIG. 19B

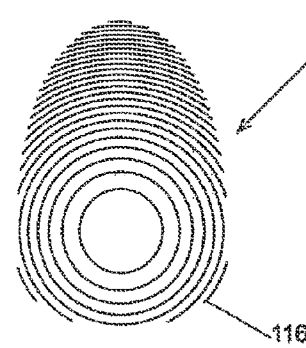

FIG. 19C

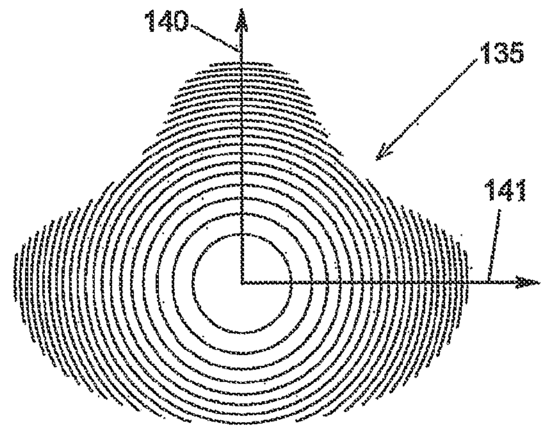

FIG. 20A

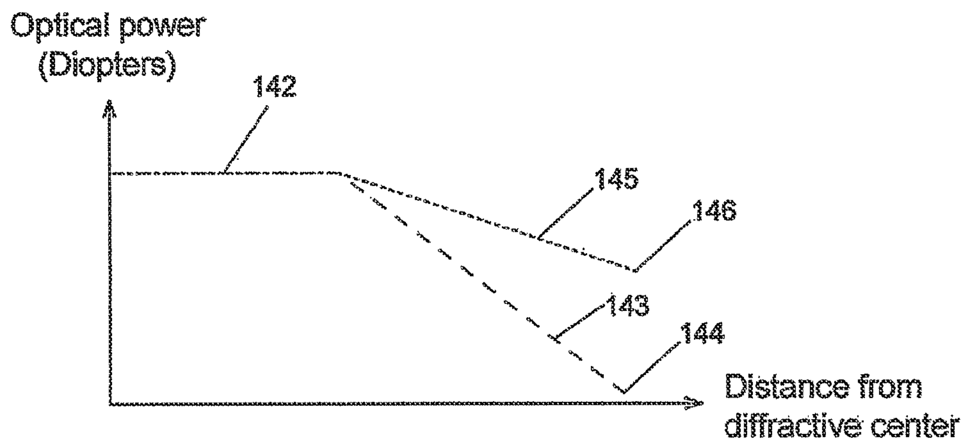

FIG. 20B

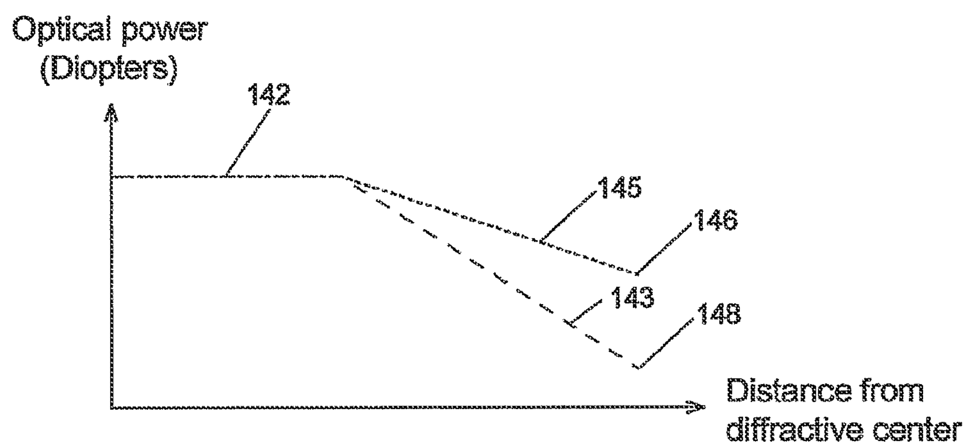

FIG. 20C

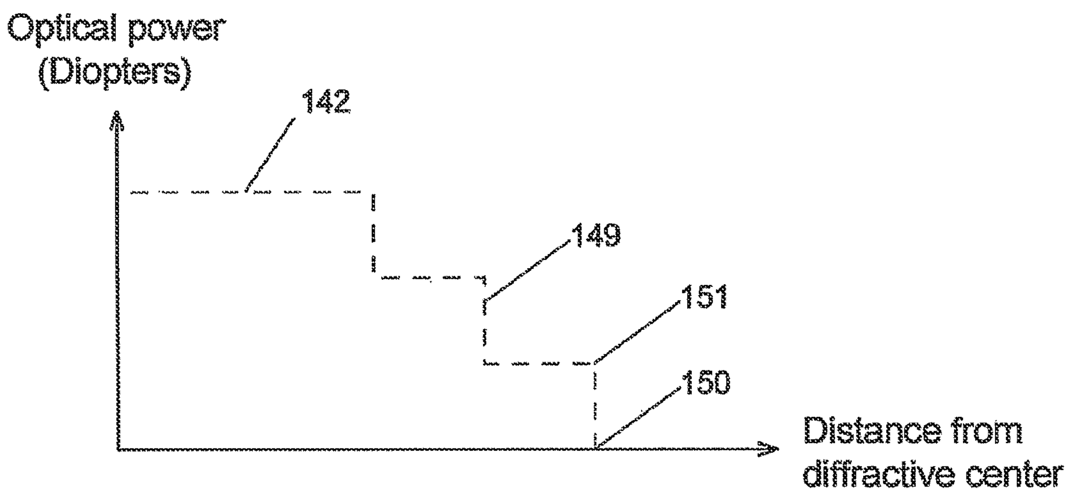
Optical power
(Diopters)
142
149
151
150
Distance from
diffractive center

FIG. 20D

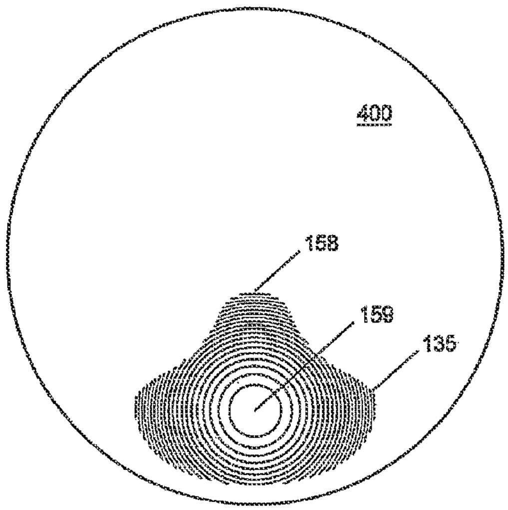

FIG. 21A

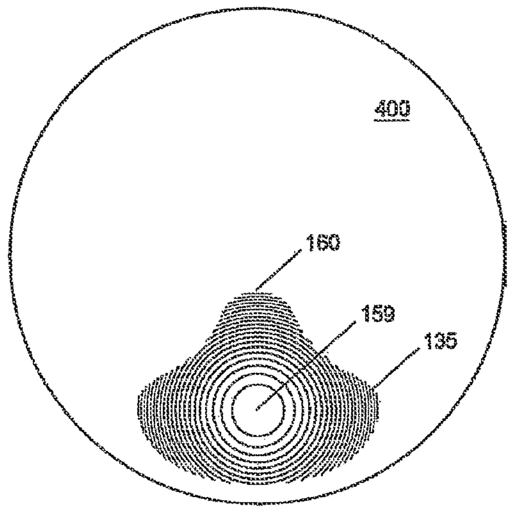

FIG. 21B

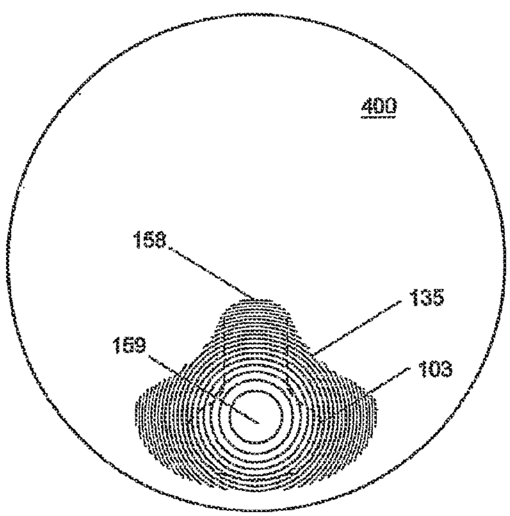

FIG. 22A

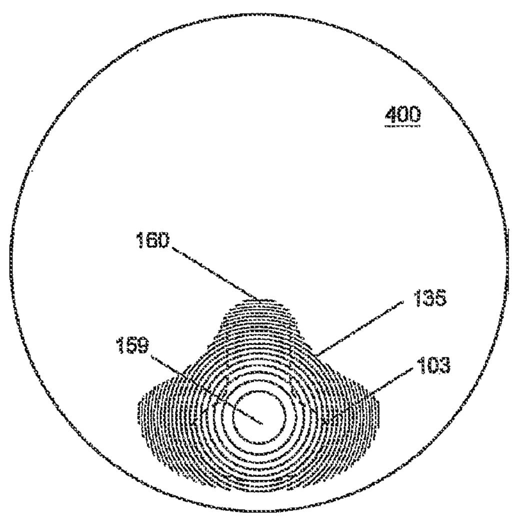

FIG. 22B

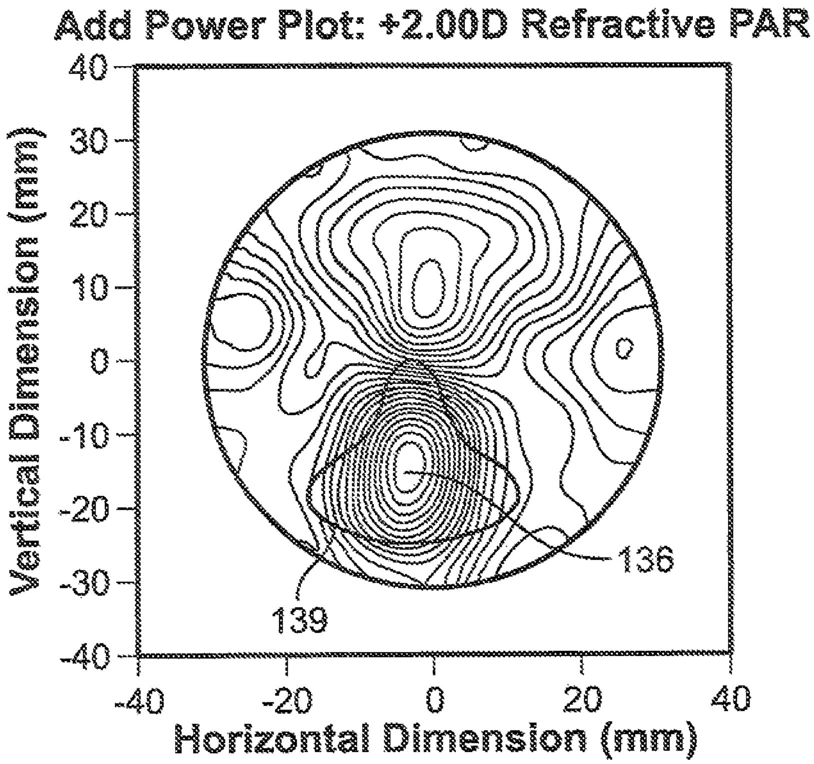

FIG. 23A

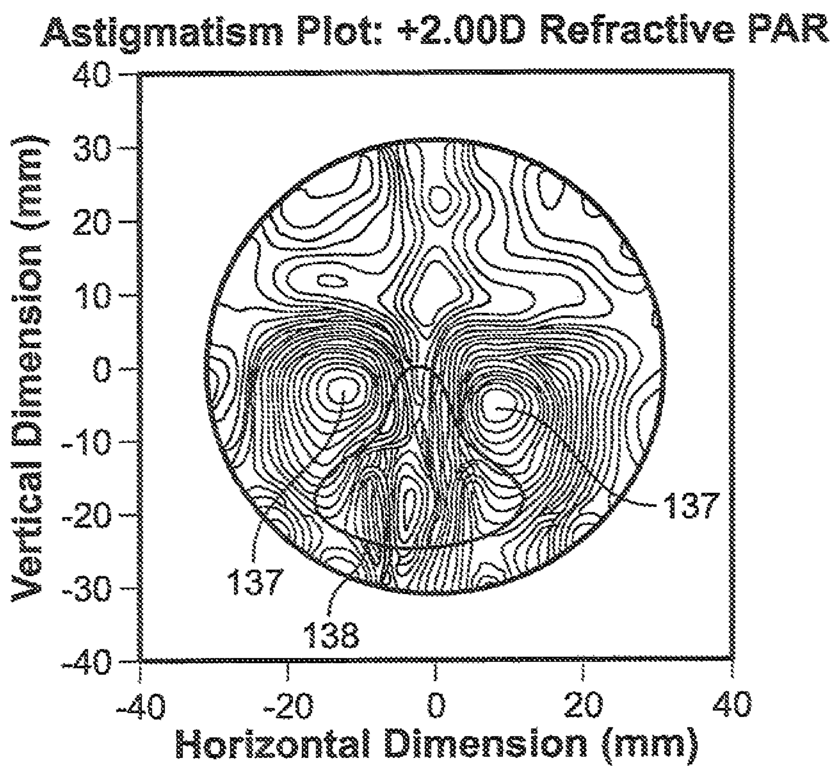

FIG. 23B

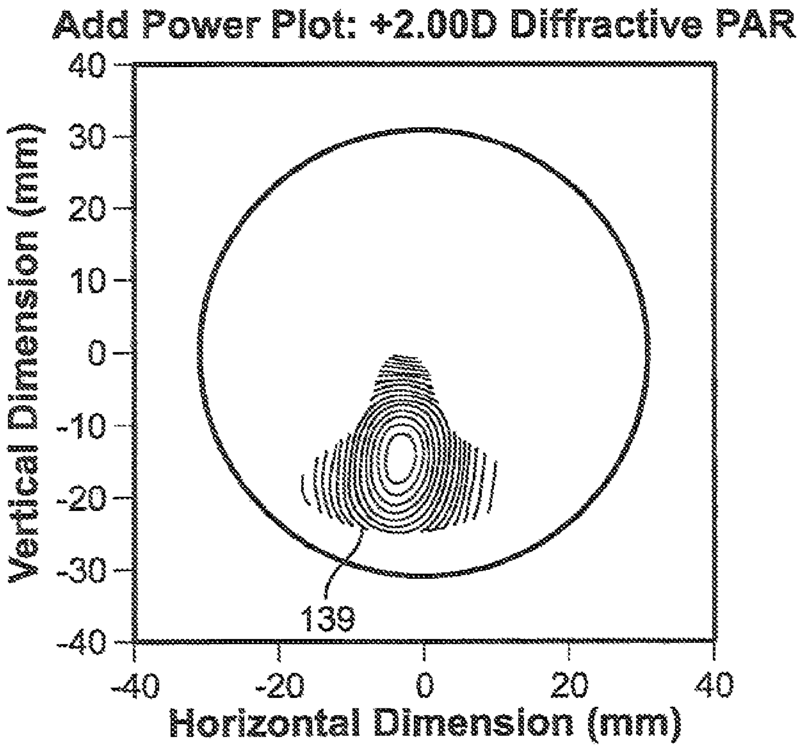

FIG. 23C

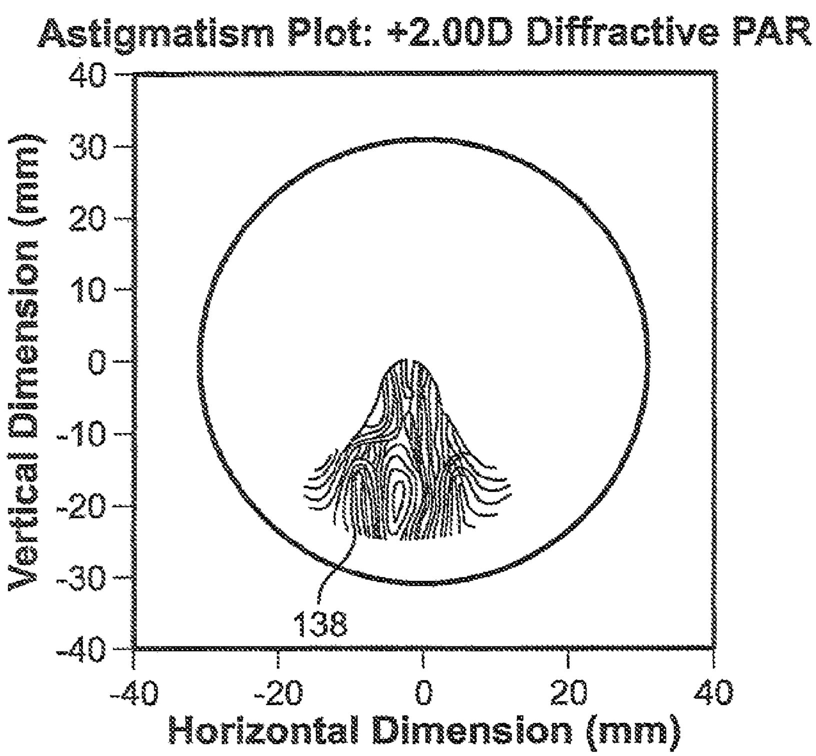

FIG. 23D

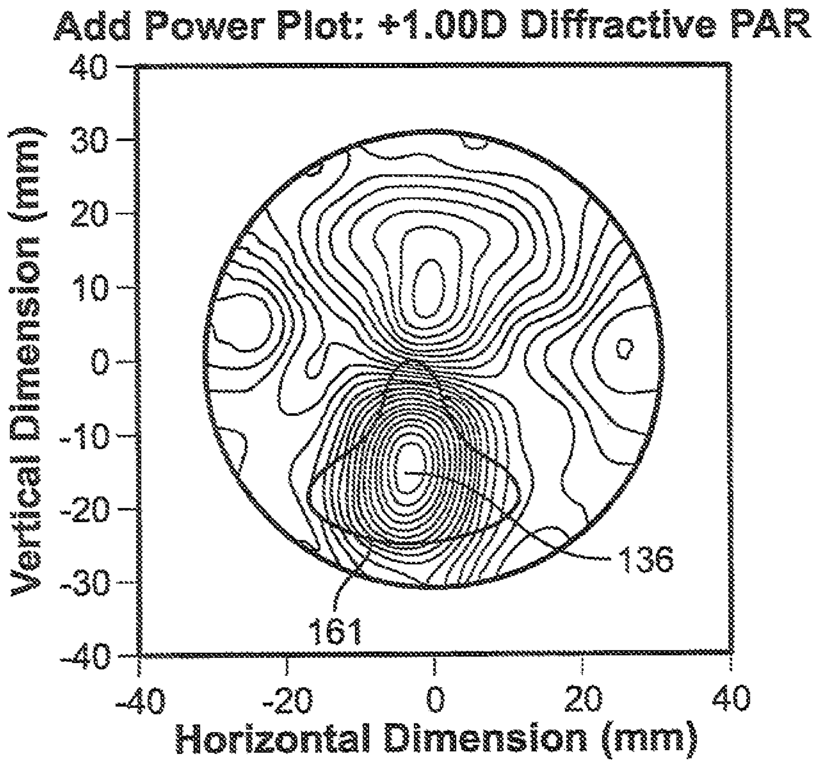

FIG. 24A

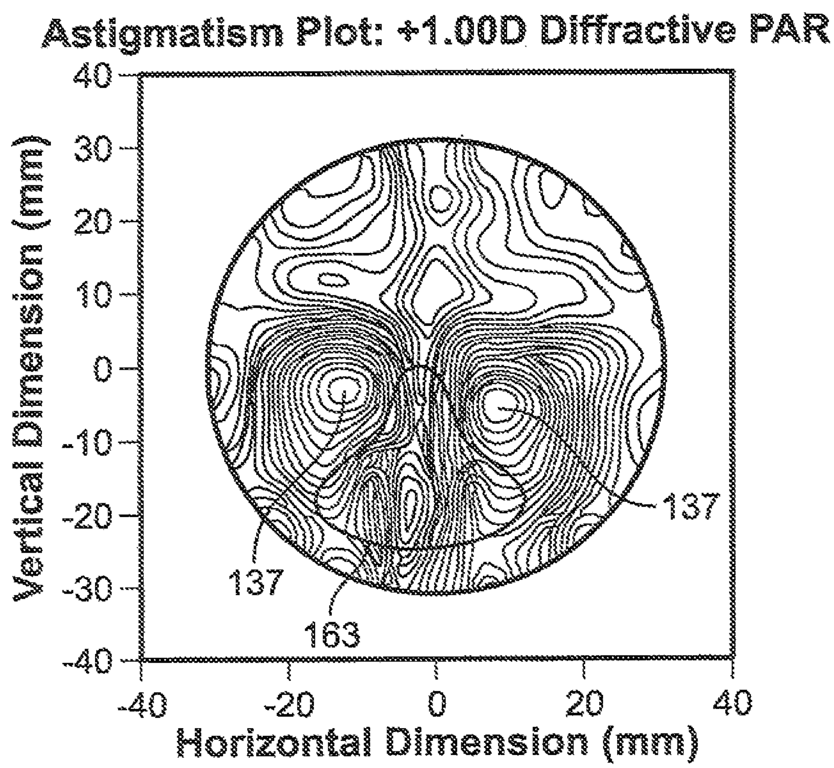

FIG. 24B

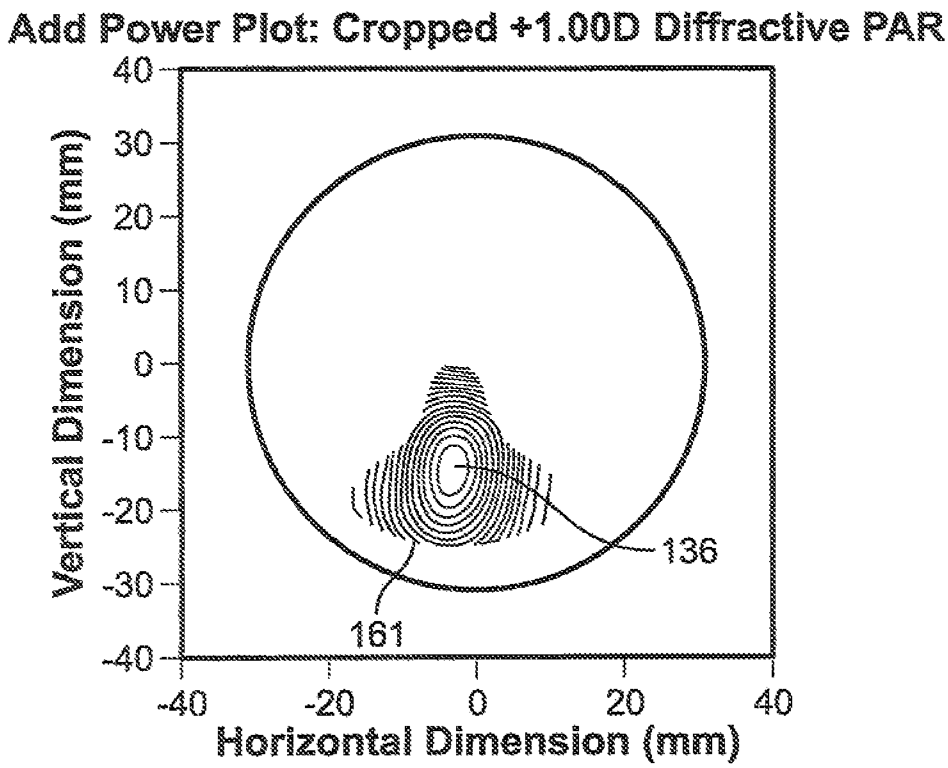

FIG. 24C

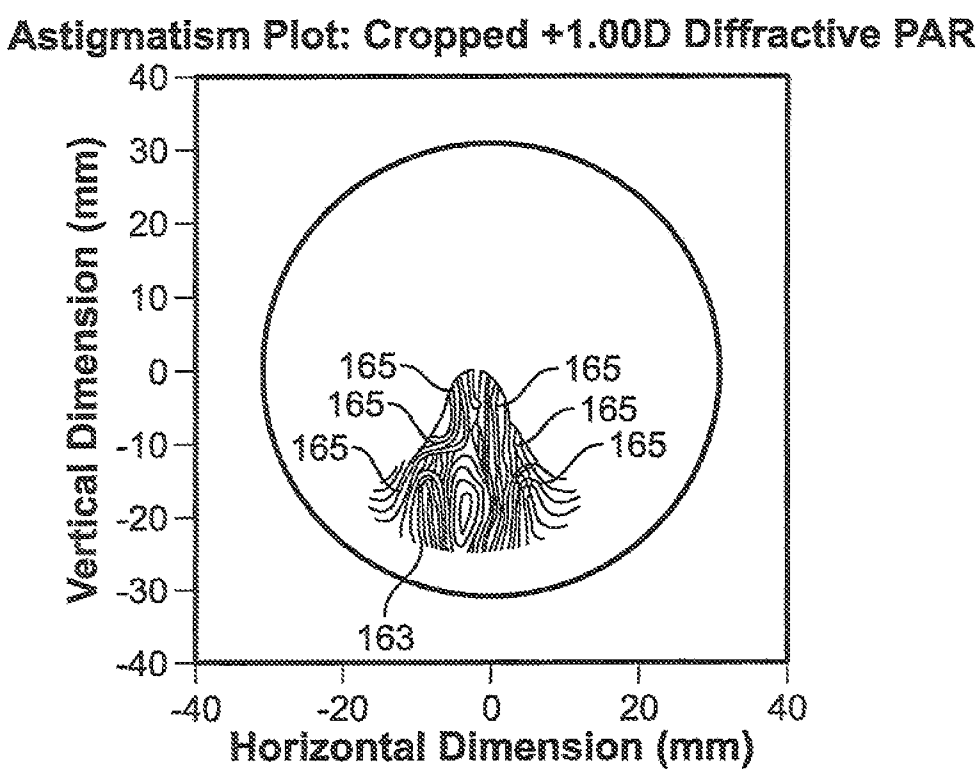

FIG. 24D

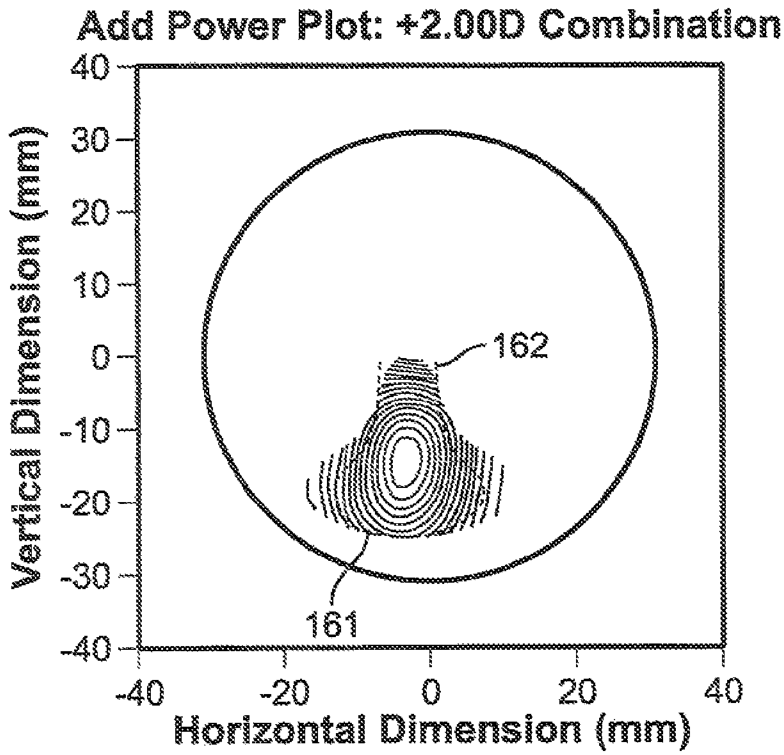

FIG. 24E

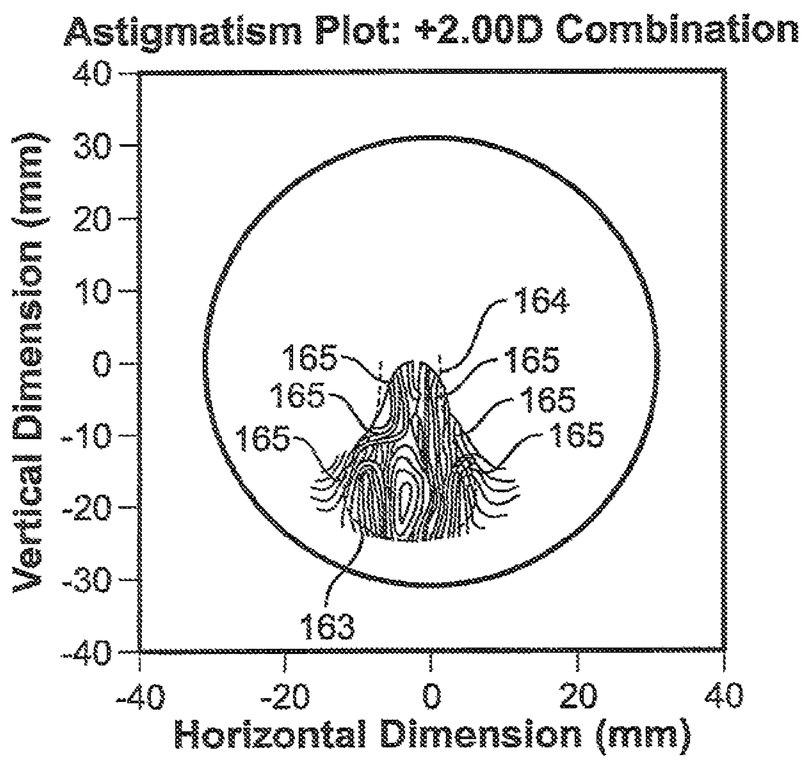

FIG. 24F

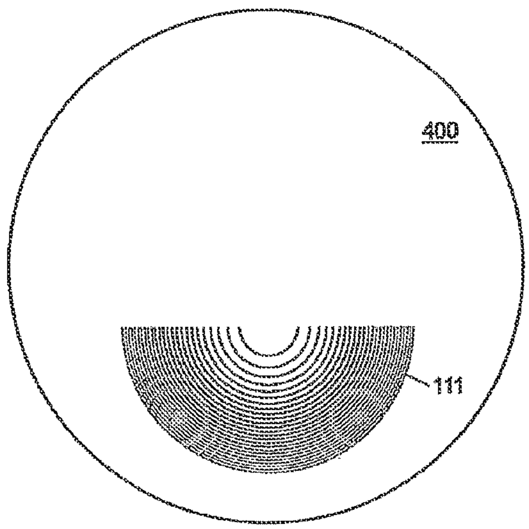

FIG. 25A

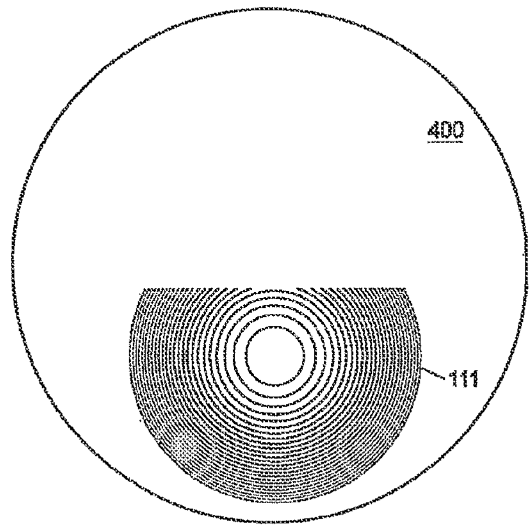

FIG. 25B

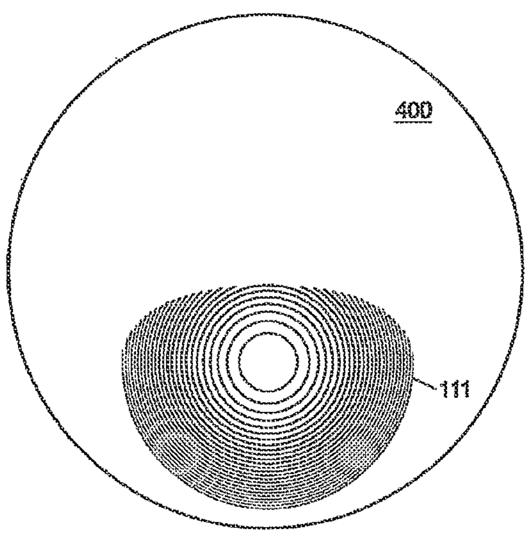

FIG. 25C

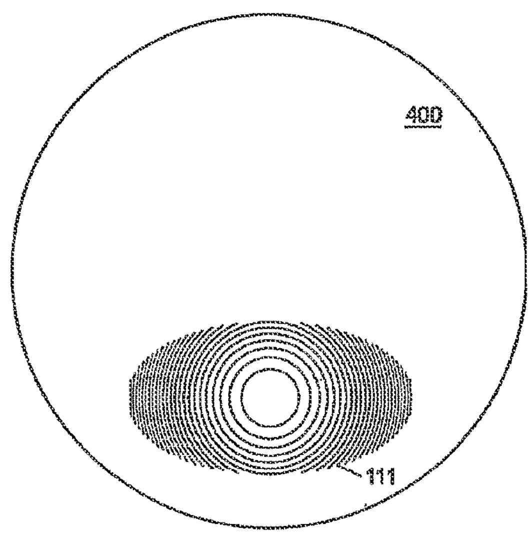

FIG. 25D

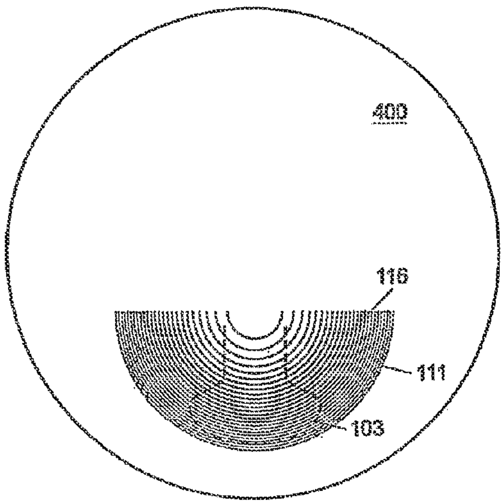

FIG. 26A

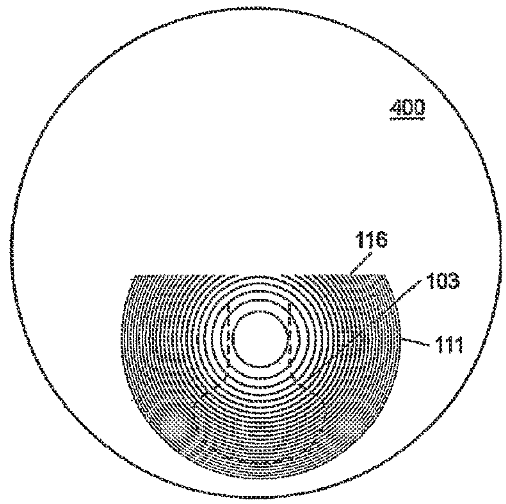

FIG. 26B

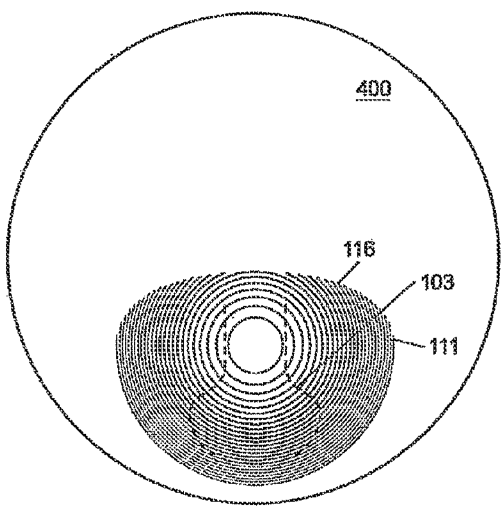

FIG. 26C

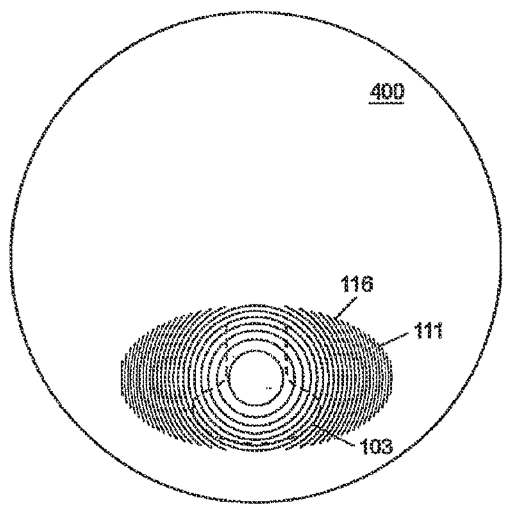

FIG. 26D

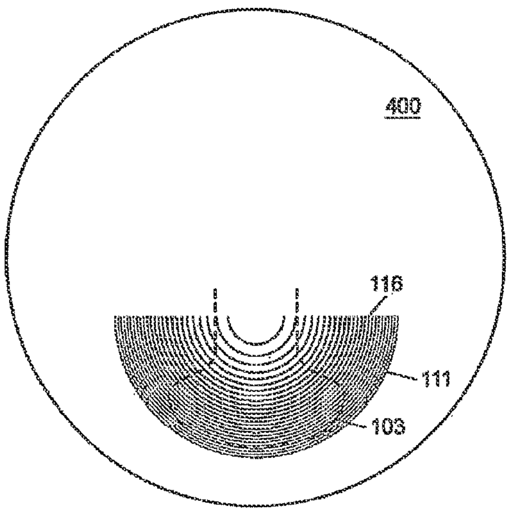

FIG. 27A

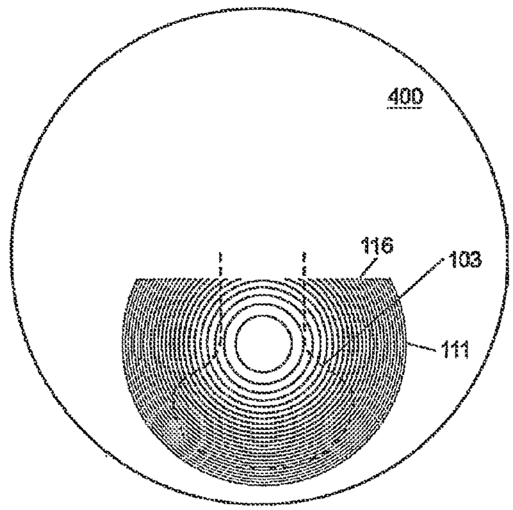

FIG. 27B

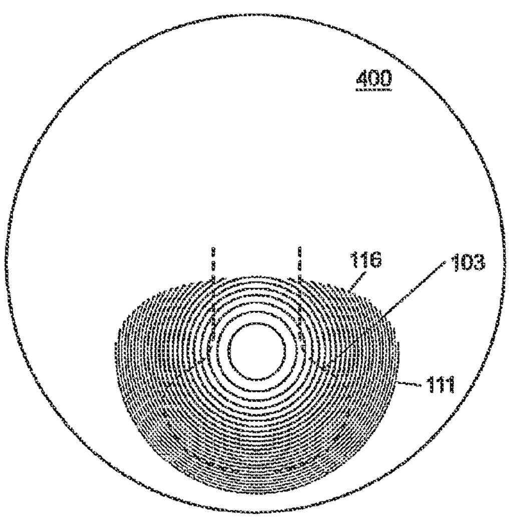

FIG. 27C

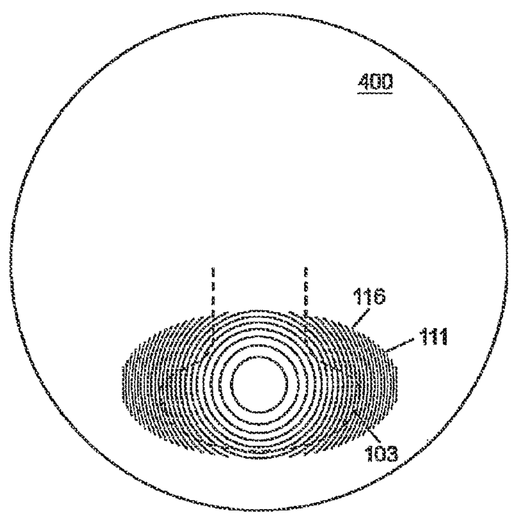

FIG. 27D

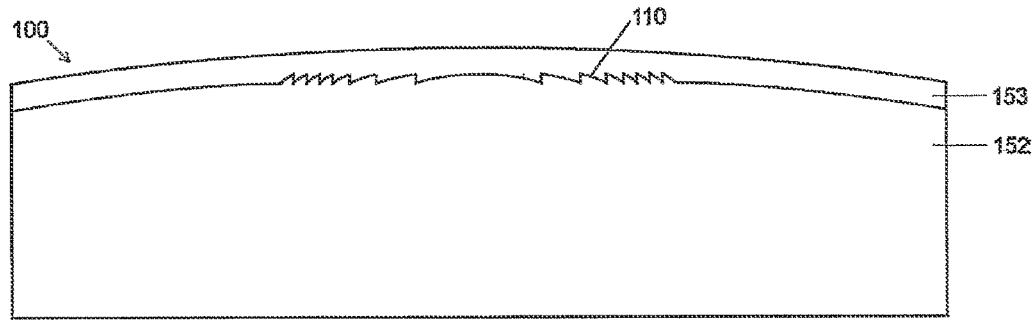

FIG. 28A

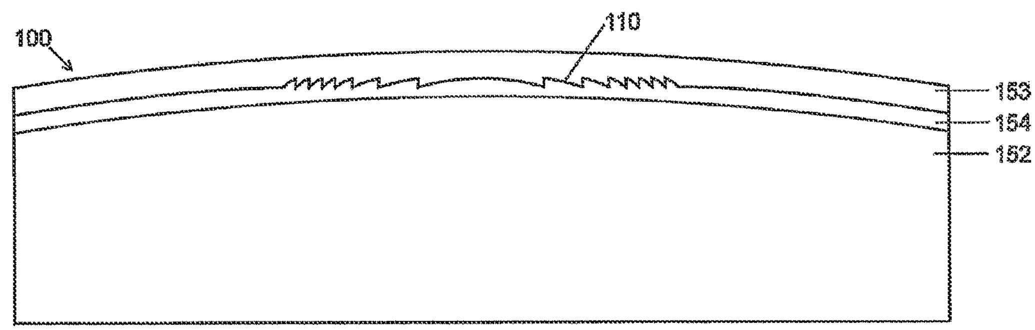

FIG. 28B

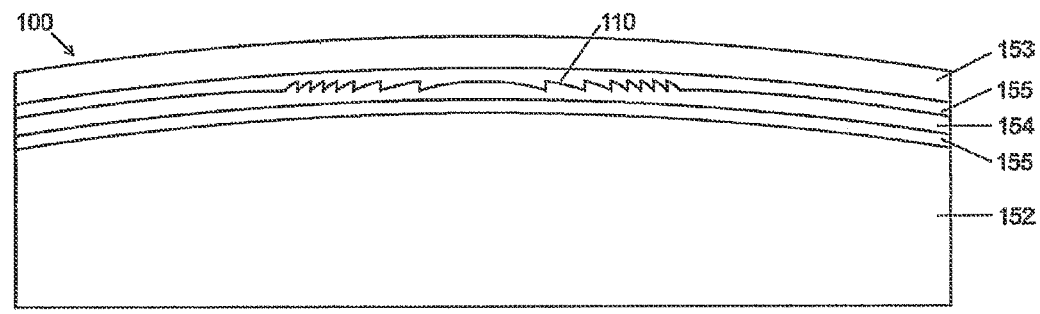

FIG. 28C

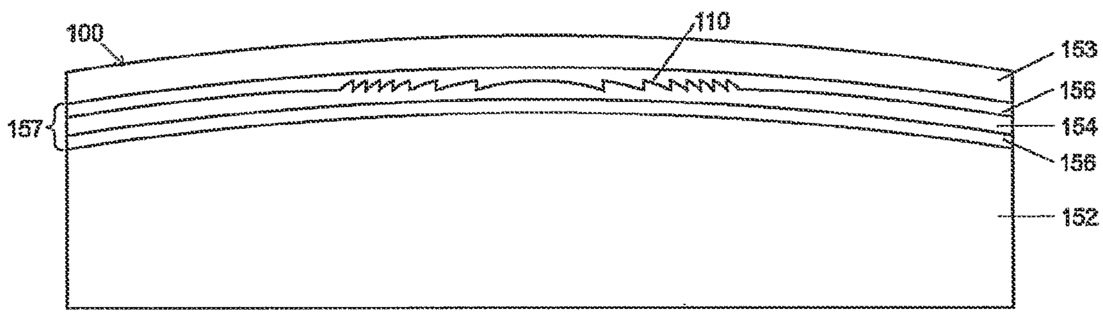

FIG. 28D

MULTIFOCAL LENS WITH A DIFFRACTIVE OPTICAL POWER REGION

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority from and incorporates by reference in their entirety the following provisional applications:

U.S. Ser. No. 60/929,570 filed on Jul. 3, 2007 and entitled "Blending of Diffraction Efficiency for Enhancing Cosmetics of Ophthalmic Lenses incorporating Diffractive Optical Elements";

U.S. Ser. No. 60/982,182 filed on Oct. 24, 2007 and entitled "Multifocal Spectacle Lens With Non-Rotationally Symmetric Diffractive Optical Power Region and Method For Making Same";

U.S. Ser. No. 60/987,556 filed on Nov. 13, 2007 and entitled "Non-Rotationally Symmetric Diffractive Optical Elements and Method for Making the Same";

U.S. Ser. No. 61/039,079 filed on Mar. 24, 2008 and entitled "Multi-Focal Opthalmic Lenses With Non-Rotationally Symmetric Diffractive Optical Power Region and Method For Making Same"; and

U.S. Ser. No. 61/039,081 filed on Mar. 24, 2008 and entitled "Multi-Focal Opthalmic Lenses With Non-Rotationally Symmetric Diffractive Optical Power Region and Method For Making Same".

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a diffractive optical power region blended in a lens by decreasing the diffractive efficiency of the diffractive optical power region near the peripheral edge thereof. The present invention also relates to a diffractive optical power region that provides a progression of optical power. The present invention further relates to both static and dynamic multifocal lenses which may use continuous or discontinuous diffractive structures.

2. Description of the Related Art

A diffractive optical power region is a region of a lens or optic that generates optical power by diffracting light. A static diffractive optical power region comprises individual surface relief diffractive structures that are typically closed concentric curves. The surface relief diffractive structures are closely spaced (e.g., by a distance on the order of the wavelengths of visible light). The surface relief diffractive structures typically have the same heights. The surface relief diffractive structures may commonly be referred to as Fresnel zones.

In general, for a given thickness of a lens or optic, diffractive optical power regions are capable of generating greater optical power than their refractive counterparts. Despite this advantage, diffractive optical power regions have several disadvantages.

One of the main disadvantages of using diffractive optical power regions is that they exhibit large amounts of chromatic aberration compared to their refractive counterparts. Chromatic aberration refers to the change in optical power that occurs as the optical wavelength is varied. Chromatic aberration in a diffractive optical power region having a constant optical power increases as the diffractive structures approach the periphery of the lens. Thus, the periphery of the diffractive optical power region exhibits the highest degree of chromatic aberration.

As a result of such chromatic aberration, a lens having a diffractive optical power region provides serious vision compromises. A vision compromise can be seen, in one approach, when the diffractive region is used to create a bifocal lens. In this approach, a diffractive optical power region may be placed in optical communication with the bottom half of an ophthalmic lens. The lens has a far distance vision correction and the diffractive optical power region provides additional optical power for near distance correction. Thus, the periphery of the diffractive optical power region forms the boundary between far distance correction and near distance correction. Since this boundary has the highest degree of chromatic aberration, a user looking across the boundary will experience the highest degree of the compromised vision.

Another disadvantage of a diffractive optical power region is that it is generally considered to be cosmetically unattractive. In the bifocal approach described above, the lens would have a sharp delineation at the boundary between the diffractive optical power region and the ophthalmic lens, similar to the line in conventional bifocals, which can be observed on a wearer. A wearer typically finds this undesirable. Since the ophthalmic industry trends towards lineless multifocal lenses (e.g., progressive addition lenses), diffractive optical power regions are less cosmetically desirable.

Thus, there is a need in the art for a diffractive optical power region that resolves the aforementioned vision and cosmetic compromises. Accordingly, there is now provided with this invention an improved lens for effectively overcoming the aforementioned difficulties and longstanding problems inherent in the art.

SUMMARY OF THE INVENTION

In an embodiment of the invention lens system may include a diffractive optical power region. The diffractive optical power region includes a plurality of concentric surface relief diffractive structures. A greater portion of light incident on a diffractive structure near the center point contributes to the optical power than light incident on a diffractive structure peripherally spaced therefrom.

In an embodiment of the invention, a lens system may include a diffractive optical power region. The diffractive optical power region includes a plurality of concentric surface relief diffractive structures. The diffractive structures include a series of crests and adjacent troughs forming a sawtooth pattern. Each concentric surface relief diffractive structure extends from a trough to a crest of the sawtooth pattern. The (e.g., vertical) distance between a first crest and a first adjacent trough near the center point is greater than the (e.g., vertical) distance between a second crest and a second adjacent trough spaced from the center point.

In an embodiment of the invention, a lens system may include a diffractive optical power region. The diffractive optical power region has a center and a peripheral edge. The diffractive optical power region focuses light to a focal point. The amount of light focused on the focal point from the center is greater than the amount of light focused on the focal point from the peripheral edge.

In an embodiment of the invention, an electro-active lens system may include a controller for applying voltages, a plurality of concentric individually addressable electrodes electrically connected to the controller, and electro-active material disposed between the individually addressable electrodes. When the controller applies voltages to the plurality of individually addressable electrodes, the refractive index of electro-active material is altered to provide an optical power. A greater portion of light incident on an individually addressable electrode near the geometric center of the plurality of individually addressable electrodes contributes to the optical power than light incident spaced from the geometric center of the plurality of individually addressable electrodes.

In an embodiment of the invention, a lens system may include a diffractive optical power region having a first region with a plurality of concentric surface relief diffractive structures for focusing light of a specific wavelength λ to a focal length f. The radius of the n^{th} concentric surface relief diffractive structure from the center point is greater than $\sqrt{2n\lambda f}$.

In an embodiment of the invention, a lens system may include a diffractive optical power region having a first region with a plurality of concentric surface relief diffractive structures for focusing light of a specific wavelength λ to a focal length f. The radius of the n^{th} concentric surface relief diffractive structure from the center point is less than $\sqrt{2n\lambda f}$.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will be understood and appreciated more fully from the following detailed description in conjunction with the figures, which are not to scale, in which like reference numerals indicate corresponding, analogous or similar elements, and in which:

FIG. **1** shows a front view of a lens **100** having a refractive progressive addition region and a diffractive optical power region.

FIG. **2**A shows a front view of the lens **100** of FIG. **1** having the static diffractive optical power region.

FIG. **2**B shows a cross-sectional view of the lens of FIG. **2**A taken along axis AA.

FIGS. **3** and **4** show front views of the lens **100** of FIG. **1** having a cropped diffractive optical power region.

FIG. **5** shows a front view of the lens **100** of FIG. **4** having an edging boundary.

FIGS. **6**A and **6**B show front views of the lens **100** of FIG. **1** having substrate layers with a continuous and a cropped diffractive optical power region, respectively.

FIG. **7** shows a path along which a cutting tool orbits the lens **100** of FIG. **6**B to cut the cropped diffractive optical power region into the substrate layer.

FIGS. **8**A-**8**I show front views of cropped diffractive optical power regions having a variety of shapes.

FIGS. **9**A and **9**B show side views of the lens **100** of FIG. **6**B having the cropped diffractive optical power region with discontinuous diffractive structures and a blend zone for blending the discontinuous diffractive structures.

FIGS. **10**A-**10**C show side views of lenses in sequential stages of etching the cropped diffractive optical power region of FIG. **6**B into a substrate layer of a lens.

FIG. **11** is a graph of a measured surface topography of a mold for manufacturing a lens having a blended cropped diffractive optical power region.

FIGS. **12**A-**12**C are graphs of the surface topography, optical power, and diffractive efficiency, respectively, of the lens mold of FIG. **11**, measured across the blend zone of the cropped diffractive optical power region.

FIGS. **13**A-**13**D are graphs of the surface topography of a lens having surface relief diffractive structures and blending functions for smoothing the surface topography of the diffractive structures.

FIG. **14**A-**14**D is a graph of the surface topography of a lens having multi-level surface relief diffractive structures and blending functions for smoothing the surface topography of the multi-level diffractive structures.

FIGS. **15** and **16** show exploded cross-sectional views of an electro-active lens.

FIGS. **17**A and **17**B show front views of the patterned electrode layer of the electro-active lens of FIG. **16**.

FIG. **18**A shows a side view of the electro-active lens of FIG. **16** having individually addressable electrodes.

FIG. **18**B shows voltages applied to the individually addressable electrodes of FIG. **18**A predetermined to cause a diffractive optical power region.

FIG. **18**C shows voltages applied to the individually addressable electrodes of FIG. **18**A predetermined to cause a diffractive efficiency blended diffractive optical power region.

FIG. **19**A shows a front view of a progressive addition diffractive optical power region.

FIGS. **19**B and **19**C show front views of the progressive addition diffractive optical power region of FIG. **19**A being cropped.

FIG. **20**A shows the cropped progressive addition diffractive optical power region of FIG. **19**B with an optical power progression along a vertical axis **140** and horizontal axis **141**.

FIG. **20**B shows graphs of the optical power along axes **140** and **141** of FIG. **20**A.

FIG. **20**C shows graphs of the optical power along axes **140** and **141** of FIG. **20**A.

FIG. **20**D shows graphs of the optical power along one or both of axes **140** and **141** of FIG. **20**A.

FIGS. **21**A and **21**B show front views of lenses **400** having the cropped progressive addition diffractive optical power regions of FIG. **19**B.

FIGS. **22**A-**22**B show front views of the lenses **400** of FIGS. **21**A and **21**B having the cropped progressive addition diffractive optical power regions of FIG. **19**B in optical communication with the refractive progressive addition region of FIG. **1**.

FIGS. **23**A and **23**B are contour plots of the optical power and astigmatism, respectively, of the refractive progressive addition region of FIG. **1**.

FIGS. **23**C and **23**D are contour plots of the optical power and astigmatism, respectively, of the cropped progressive addition diffractive optical power region of FIG. **19**B approximating the optical power progression of the refractive progressive addition region of FIG. **1**.

FIGS. **24**A and **24**B are contour plots of the optical power and astigmatism, respectively, of the progressive addition diffractive optical power region of FIG. **19**A.

FIGS. **24**C and **24**D are contour plots of the optical power and astigmatism, respectively, of the cropped progressive addition diffractive optical power region of FIG. **19**B.

FIGS. **24**E and **24**F are contour plots of the optical power and astigmatism, respectively, of the cropped progressive addition diffractive optical power region of FIG. **19**B in combination with a refractive progressive addition region of FIG. **1**.

FIGS. **25**A-**25**D show front views of the lenses **400** of FIGS. **21**A-**21**B having the cropped diffractive optical power region with constant optical power.

FIGS. **26**A-**26**D show front views of the lenses **400** of FIGS. **25**A-**25**D having the cropped diffractive optical power region with constant optical power in optical communication with the refractive progressive addition region of FIG. **1**.

FIGS. **27**A-**27**D show front views of the lenses **400** of FIGS. **26**A-**26**D having the refractive progressive addition region located at least partially outside of the cropping boundary of the diffractive optical power region.

FIGS. **28**A-**28**D show side views of the lenses **100** of FIGS. **3** and **4**.

DETAILED DESCRIPTION OF THE INVENTION

A diffractive optical power region in a lens may be either static or dynamic. A static diffractive optical power region has an optical power that is fixed at any point. The optical power does not change by the application of electrical or other power. In contrast with a static diffractive optical power region, a dynamic diffractive optical power region has an alterable optical power at one or more positions along the diffractive region. The dynamic diffractive optical power region typically includes a plurality of conducting structures, e.g., pixels or electrode rings, electrically connected to a controller having an electrical power supply. The controller applies electrical power to the conducting structures to create a voltage pattern across the dynamic diffractive optical element, which is predetermined to diffract light to cause the desired optical power.

FIG. **1** shows a front view of a lens **100** having a refractive progressive addition region **103** and a diffractive optical power region **104**, in accordance with a prior art design. The lens is a multifocal lens having at least a first optical power provided by the diffractive optical power region **104** alone and at least a second optical power provided by the combination of the refractive progressive addition region **103** and the diffractive optical power region **104**.

The refractive progressive addition region **103** provides a gradient of continuously monotonically increasing positive optical power. The refractive progressive addition region **103** provides optical power by the refraction of light. The refractive progressive addition region **103** is shown in a static lens. Thus, although there is a change in optical power at different points along the surface of the refractive progressive addition region **103**, at any single point, the optical power of the static lens is fixed (i.e., does not change by the application of electrical or other power).

The diffractive optical power region **104** provides optical power by the diffraction of light. The diffractive optical power region **104** is shown in a static lens. The static diffractive optical power region **104** includes a plurality of diffractive structures **110** that are concentric with a center point **105**. When the diffractive optical power region **104** is static, the diffractive structures **110** are typically surface relief diffractive structures typically having a sawtooth cross-sectional pattern. The diffractive optical power region **104** is shown to provide a constant optical power, although any optical power may be achieved. The optical power of the diffractive optical power region **104** is determined by the spacing between each surface relief diffractive structure **110**. To achieve a constant optical power, the radii of the surface relief diffractive structures **110** are defined by:

$$\rho_n=\sqrt{2n\lambda f} \tag{1}$$

where ρ_n is the radius of the n^{th} concentric surface relief diffractive structure **110** from the diffractive geometric center **105**, f is the design focal length (i.e., the inverse of the constant optical power of the diffractive region, expressed in diopters [m^{-1}]), and λ is a design wavelength.

Although a static diffractive optical power region **104** is shown in FIG. **1**, it is understood that in other embodiments of the invention, a dynamic diffractive optical power region may be used. A dynamic diffractive optical power region typically employs one or more voltages predetermined to achieve electro-active diffractive optical effects equivalent to those described in reference to the static approach of FIG. **1**.

The diffractive optical power region **104** is in optical communication with the refractive progressive addition region **103**. The diffractive optical power region **104** at least partially, and preferably largely, overlaps the refractive progressive addition region **103**. When used in combination, the refractive progressive addition region **103** provides a wearer with optical power less than the wearer's total needed near distance optical power correction and the diffractive optical power region **104** provides the remaining optical power to provide the wearer's total needed near distance optical power correction. Using the diffractive optical power region **104** to supplement the optical power of the refractive progressive addition region **103** reduces the overall optical power of the refractive progressive addition region **103**. Since unwanted astigmatism is known to increases at a greater than linear rate as a function of the total add power of a refractive progressive addition region, supplementing the optical power of the refractive progressive addition region **103** reduces these astigmatic and other unwanted effects, such as, distortion, perceptual blur, or swim.

The lens **100** includes a far distance vision region **107**, a far-intermediate vision region **108**, and an intermediate to near distance vision region **109**. The intermediate to near distance vision region **109** may be located, for example, in the region where the refractive progressive addition region **103** has a maximum add power and coincides with the center of the diffractive optical power region **104**. The far-intermediate distance vision region **108** may be located, for example, in the region where the refractive progressive addition region **103** has less than its maximum add power and coincides with the diffractive optical power region **104**. Alternatively, the far-intermediate distance vision region **108** may be located, for example, in the region where the refractive progressive addition, region **103** is absent and the diffractive optical power region **104** is present. The far distance vision region **107** may be located, for example, in the region where the refractive progressive addition region **103** and the diffractive optical power region **104** are absent. Near distance vision (e.g., for reading) typically describes vision at distances in a range of from approximately 10" to approximately 16" from the eye. Intermediate distance vision (e.g., for computer and other office work) typically describes vision at distances in a range of from approximately 16" to approximately 24" from the eye. Far-intermediate vision describes vision at distances in a range of from approximately 24" to approximately 6' from the eye. For example, the optical power for correcting far-intermediate vision is approximately 50% (and preferably approximately 40%) or less of the optical power for correcting near distance vision.

The lens **100** has a geometric (or physical) center **102** and a fitting point **101**. Typically, the far distance vision region **107** is located on the upper half of the viewing region of the lens **100** above the fitting point **101**. The fitting point **101** is designed to coincide with the location of the wearer's pupil and typically marks the start of the optical power progression (along the progressive addition region **103**) from the far distance vision region **107** to the intermediate to near distance vision region **109**.

The diffractive optical power region is shown in FIG. **1** to be located below the fitting point **101** and overlapping the geometric center **102** of the lens **100**. However, it may be appreciated that the diffractive optical power region **104** can be located anywhere on the lens **100**. For example, the diffractive optical power region **104** can be centered at the fitting point **101** of the lens **100**, such that the diffractive structures **110** are concentric with the fitting point **101**.

FIG. **2**A shows a front view of the lens **100** of FIG. **1** having the static diffractive optical power region **104**, in accordance with a prior art design. The static diffractive optical power region **104** includes a plurality of surface relief diffractive structures **110** that are concentric with a diffractive geometric center **105**. The surface relief diffractive structures **110** are continuous closed curves, which, although shown as circular, can be shaped as any closed curves such as an ellipse.

FIG. **2**B shows a cross-sectional view of the lens **100** of FIG. **2**A taken along axis AA, in accordance with a prior art design. FIG. **2**B shows the topographical profile of the diffractive optical power region **104** of FIG. **2**A formed from the diffractive structures **110**. The topographical profile of the surface relief diffractive structures **110** shows a sawtooth pattern. The portion of a surface relief diffractive structure **110** at the maximum height of the structure is referred to as a “diffractive peak” and the portion of a surface relief diffractive structure **110** at the minimum height of the structure is referred to as a “diffractive trough”. The heights of the surface relief diffractive structures **110** are shown to be constant.

However, the radial widths of the diffractive structures **110**, that is the distance from one peak to an adjacent peak (or one trough to an adjacent trough), decrease as the diffractive structures **110** extend radially toward the periphery of the diffractive optical power region **104**. A radial width is shown as **112** in FIG. **2**B. As described above, as the radial widths **112** of the diffractive structures **110** decrease, the chromatic aberration increases. Accordingly, the peripheral region of the diffractive optical power region **104** exhibits the greatest degree of chromatic aberration.

Referring again to FIG. **1**, the diffractive optical power region **104** includes a compromised vision region **106**. The compromised vision region **106** is a region that causes incident light to experience chromatic aberration greater than a predetermined threshold. Typically, the compromised vision region **106** is located near at least a portion of the periphery of the diffractive optical power region **104**. The compromised vision region **106** may form a sharp delineation at its boundary with the remainder of the lens **100**.

As shown in FIG. **3**, to minimize these cosmetic and vision compromises, the compromised vision region depicted in FIG. **1** can be removed from the lens **100**, in accordance with an aspect of the present invention. In one approach, at least a portion of the peripheral edge of a diffractive optical power region can be physically “cropped” to exclude the compromised vision region. Typically, cropping a diffractive optical power region does not change the shape of individual surface relief diffractive structures that form the region. For example, the individual surface relief diffractive structures remain circular and concentric with the center point **105**. However, cropping does change the shape of a diffractive optical power region as a whole by defining a new peripheral edge thereof. Prior to cropping, the peripheral edge, and thus, the dimensions of the diffractive optical power region are defined by the most peripheral surface relief diffractive structure (i.e., the circle with the largest diameter). Cropping cuts the most peripheral surface relief diffractive structure(s), thereby interrupting the closed curved shape thereof. The interrupted surface relief diffractive structure(s) are no longer closed curves, but arcs or segments thereof. The peripheral edge of the cropped diffractive optical power region includes one or more surface relief diffractive structures that are shaped as arcs (no longer forming closed curves).

FIGS. **3** and **4** show front views of the lens **100** of FIG. **1** having a cropped diffractive optical power region **111**, in accordance with various aspects of the present invention. A “cropped diffractive optical power region” is a diffractive optical power region having one or more diffractive structures **113** that do not form closed curves. Instead the diffractive structures are shaped as arcs, e.g., closed segments of complete closed curves (e.g., circles or ellipses). These diffractive structures **113** may be referred to as “discontinuous”. The cropped diffractive optical power region **111** can also have surface relief diffractive structures that form complete closed curves. Diffractive structures that form complete closed curves are referred to as “continuous”. Diffractive structures **110** depicted in FIG. **1**, e.g., can be considered continuous. Continuous diffractive structures are typically located radially interior to the discontinuous diffractive structures **113**. The peripheral boundary of the cropped diffractive optical power region **111** is referred to as the “cropping boundary”.

Typically, the portions of continuous diffractive structures that are not present (i.e., cropped) in the discontinuous diffractive structures **113** are those that, if present, would have the highest degree of spherical aberration. Thus, the exclusion of these portions in a cropped diffractive optical power region provides fewer vision compromises than a comparable diffractive optical power region having the same optical power (i.e., the same radial spacing of diffractive structures) that is not cropped (i.e., having continuous diffractive structures).

Although, the cropped diffractive optical power region **111** is shown to have a “D” shape and an elliptical shape in FIGS. **3** and **4**, respectively, it may be appreciated that the cropped diffractive optical power region may have any shape.

FIG. **5** shows a front view of the lens **100** of FIG. **4** having an edging boundary **114**, in accordance with an aspect of the present invention. The edging boundary **114** is a boundary to which the lens **100** can be edged to be mounted in a spectacle lens frame, e.g., without damaging or altering the optical properties of the cropped diffractive optical power region **111**. Edging to the edging boundary may be particularly important in embodiments shown in FIGS. **15** and **16**, when the diffractive optical power region is formed from an electro-active element, in accordance with an aspect of the present invention. In such embodiments, edging the diffractive optical power region may cause physical damage to the electro-active element, such as leaking of electro-active material.

FIGS. **6**A and **6**B show front views of the lens **100** of FIG. **1** having substrate layers **115** with a continuous diffractive optical power region **104** and a cropped diffractive optical power region **111**, respectively, in accordance with various aspects of the present invention. The substrate layer **115** may be composed of any transparent optical material suitable for use in an ophthalmic spectacle lens such as, e.g., ultra-violet (UV) and/or thermally cured monomer resins, or thermoplastics. The diffractive optical power region **111** may be formed into a tool for casting, stamping, embossing, or thermo-forming the diffractive optical power region **111** into a transparent optical material suitable for an ophthalmic spectacle lens using methods known in the art. Such tools are typically composed of metal, e.g., a nickel coated aluminum, stainless steel material, or any other known material(s).

FIG. **6**A shows the substrate layer **115** having closed curves forming the continuous diffractive structures **110** of the diffractive optical power region **104**.

FIG. **6**B shows the substrate layer **115** having discontinuous curves forming the discontinuous diffractive structures **113** of the cropped diffractive optical power region **111**. The cropped diffractive optical power region **111** also has continuous closed curves forming the continuous diffractive structures **110**. FIG. **6**B has a cropping boundary **116** (i.e., the outer boundary of the cropped diffractive optical power region **111**). The cropping boundary **116** lies completely within the peripheral edge of the substrate layer **115**.

Various methods and devices may be used to cut diffractive structures **113** into the substrate layer **115** of FIGS. **6**A and **6**B so that the diffractive structures may be recessed into the lens or protruding out from the lens.

In one method, a diamond machine tool is used to cut or etch grooves directly into the substrate layer to form the curves of the diffractive structures. Alternatively, the grooves may be cut into a mold tool (or mold master for later replication) for casting or embossing the substrate layer. The lathe may utilize a diamond tipped cutting tool that is angled perpendicular to an outer surface of the substrate layer. The lens or mold tool is rotated and the cuffing tool may be moved along a direction parallel to the axis of the lens rotation (normal to the plane of rotation). When the cutting tool, is moved inwards towards the lens, the tool penetrates the substrate layer, removing material from the layer. Likewise, when the cutting tool is moved away from the lens, the tool releases from the substrate layer and no material is removed from the layer. Thus, as the lens or mold tool rotates, the cutting tool may penetrate the lens to form rotationally symmetric (i.e., circular) grooves. Alternatively, elliptical grooves may be cut into the lens by rotating the lens about an axis and moving the cutting tool in a line as the cutting tool penetrates the lens surface at a constant depth. Similarly, the cutting tool may be moved in other patterns to cut grooves having other curvatures.

The discontinuous diffractive structures **113** of FIG. **6**B are cut into the substrate layer as shown in FIG. **7**.

FIG. **7** shows a path along which a cutting tool orbits the front view lens **100** of FIG. **6**B to cut a cropped diffractive optical power region **111** into the substrate layer **115**, in accordance with an aspect of the present invention. The orbital path is marked by solid paths **117** indicating the tool is cutting into the substrate layer **115** and dashed paths **118** indicating the tool is not cutting into the substrate layer **115**. The cutting tool weaves into and out of the substrate layer **115**, entering the lens **100** at an entry point **119** to initiate cutting and exiting the lens **110** at an exit point **120** to stop cutting. The locations of the entry point **119** and the exit point **120** define where the diffractive structures are cut into the substrate layer **115** and where they are not. The entry point **119** and the exit point **120** form the ends of the curved arcs of the discontinuous diffractive structure **113**. The entry point **119** and the exit point **120** lie on and define the cropping boundary **116**. Interior to the cropping boundary **116**, the cutting tool engages the substrate layer **115** and cuts the grooves of the discontinuous surface relief diffractive structure **113** (along the solid paths **117**). Exterior to the cropping boundary **116**, a mechanical actuator typically removes the tool from the substrate layer **115** as the cutting tool orbits the lens when it is unengaged (along the dashed paths **118**). Thus, the discontinuous diffractive structures **113** of the cropped diffractive optical power region **111** are cut into the substrate layer **115**. The cropped diffractive optical power region **111** can be cut into the substrate layer **115** with a cutting tool using fast-tool servo or slow-tool servo techniques, although other known techniques and tools for cutting the substrate layer **115** can be used. The area exterior to the cropping boundary **116**, which is not cut, typically includes the compromised vision region **106** shown in FIG. **1**, near the peripheral edge of the continuous diffractive optical power region **104**. The compromised vision region **106** may be predicted to, if formed, provide a high degree of chromatic aberration.

Although the orientation of rotation of the lens **100** in FIG. **7** is shown to be counterclockwise (indicated by arrows at the entry and exit points **119** and **120**) it may be appreciated that the orientation can be reversed to clockwise. If the orientation of rotation of the lens **100** is reversed, the positions of the entry point **119** and the exit point **120** are also reversed.

Although, FIG. **7** is described in reference to elliptically shape cropped diffractive optical power region **111**, it may be appreciated that a similar process may be used to crop a diffractive optical power region to have any rotational shape. In one approach, the entry point **119** and the exit point **120** may be positioned at alternative locations on a surface of the lens **100** to define a cropping boundary having a desired shape and size.

FIGS. **8**A-**8**I show front views of cropped diffractive optical power regions **111** having a variety of shapes, in accordance with various aspects of the present invention. It is to be understood that other shapes and sizes of cropped diffractive optical power regions **111** are possible using the techniques described herein. The cropped diffractive optical power regions **111** shown in FIGS. **8**A-**8**I may also be made coincident with the continuous diffractive optical power region **104** of FIG. **6**A.

The continuous diffractive structures **110** of the diffractive optical power region **104** of FIG. **6**A can be cut into the substrate layer **115** by penetrating the layer with the cutting tool at different radii while the lens **100** rotates. The lens **100** may rotate at least a full rotation (e.g., at least 360°) relative to the cutting tool before the cutting tool is moved to the next radius. Alternatively, the cutting tool may move continuously outward as the lens rotates in the lathe, forming spiraling groove(s).

However, having a discontinuity may introduce other optical difficulties. Typically, when the cutting tool cuts with an instantaneous puncture or release, a sharp discontinuous gradient in depth of the substrate layer **115** forms along the cropping boundary **116** of the cropped diffractive optical power region **111**. The discontinuous gradient in depth causes an unwanted line along the cropping boundary **116**. To solve this problem, a blend zone may be added to blend this boundary.

Conventional blend zones typically blend optical power. Optical power is blended between a diffractive region and another region by altering the radial positions of the diffractive structures. A more detailed description of such embodiments may be found in U.S. application Ser. No. 11/595,971 filed on Nov. 13, 2006 and entitled "Electro-Active Ophthalmic Lens Having an Optical Power Blending Region", which is incorporated herein by reference in its entirety. The optical power of the diffractive region generally decreases to zero where the diffractive structures meet the rest of the lens. Thus, an abrupt change in optical power and thus, any line, at this boundary between the diffractive structures and the rest of the lens is eliminated. Although this blend zone reduces the visibility of the line from the lens, it has other further disadvantages. One disadvantage is that, as the optical power decreases to zero in the blend zone, the blend zone has little optical use.

To solve this problem, a blend zone is proposed that blends the diffractive optical power region by reducing the diffractive efficiency thereof to zero extending radially towards the peripheral edge thereof. Diffraction efficiency is the fraction of incident light that is directed into the desired diffraction order (i.e., the design optical power or focal length of the lens). As the diffractive efficiency of the diffractive optical power region approaches zero, the fraction of light that is focused by the diffractive optical power region is likewise reduced to zero. Thus, at the peripheral edge of the diffractive optical power region, the diffractive efficiency is blended to zero and the optical effect of the region is likewise blended to zero, forming a gradual and lineless boundary.

The diffraction efficiency, η, at the design focal length is mathematically defined as:

$$\eta = \left\{ \frac{\sin\left[\left[1 - \frac{\Delta\phi}{2\pi}\right]\pi\right]}{\left[1 - \frac{\Delta\phi}{2\pi}\right]\pi} \right\}^2 \tag{2}$$

where Δϕ is the phase delay generated by a diffractive optic, such as, the surface relief diffractive structures.

Equation (2) shows that the diffraction efficiency, η, is 1 (1.00% of incident light is focused to the design focal length) when the phase delay, Δϕ, is 2π, and zero (no light is focused to the design focal length) when the phase delay, Δϕ, is zero.

When a surface relief diffractive structure having a first refractive index, n_1, is in contact with another optical structure having a second refractive index, n_2, the phase delay Δϕ is defined as:

$$\Delta\phi = 2\pi \frac{n_1 - n_2}{\lambda} d \tag{3}$$

where λ is the incident optical wavelength d is the depth of a diffractive structure.

Together equations (2) and (3) show that as the depth, d, of the diffractive structure is smoothly blended to zero, the diffraction efficiency is likewise blended to zero.

Thus, a diffraction efficiency blend zone can be formed by blending the heights of the diffractive structures.

FIGS. **9**A and **9**B show side views of a single discontinuous curve of a discontinuous diffractive structure **113** and a blend zone **123** for blending the discontinuous curve, in accordance with various aspects of the present invention. The blend zone **123** is achieved by varying the heights of the discontinuous curve at the cropping boundary of the cropped diffractive optical power region. As the cutting tool **121** approaches the cropping boundary, the cutting tool enters and exits the substrate layer **115** over the blend zone **123** having a distance, w, predetermined to cause a continuous gradient in the height of the discontinuous curve (e.g., from a minimum (0) to a maximum value). This continuous gradient in depth is predetermined to blend the cropped diffractive optical power region to form a lineless cropping boundary. The distance, w, for the entry and exit of the cutting tool is in a range of from, e.g., approximately 0.5 millimeters (mm) to approximately 4 mm, and is preferably approximately 1 mm, although any distance, w can be used.

In FIG. **9**A, the cutting tool **121** cuts the substrate layer along a path **124** predetermined to form a protruding discontinuous curve. In FIG. **9**B, the cutting tool **121** cuts the substrate layer along a path **125** predetermined to form a recessed discontinuous curve. Although the discontinuous curves of FIGS. **9**A and **9**B are physically inverted, they are generally optically equivalent.

In contrast to FIGS. **7**, **9**A and **9**B, which show a blended cropped diffractive optical power region formed using a cutting tool, the blended cropped diffractive optical power region may alternatively be etched using known semiconductor processing tools and techniques, as shown in FIGS. **10**A-**10**C.

FIGS. **10**A-**10**C show side views of lenses **1000**-**1002**, respectively, in sequential stages of etching a cropped diffractive optical power region onto a substrate layer of a lens, in accordance with various aspects of the present invention.

FIG. **10**A shows a side view of a lens **1000** having a flat substrate layer **128** coated with an etch resist layer **127**. The etch resist layer **127** may be composed of e.g., a photoresist, although other materials may be used. The substrate material may be the desired final material for the lens or may be a mold material from which the desired diffractive structures may be cast, stamped, thermo-formed, or embossed.

FIG. **10**B shows a side view of a lens **1001** having the flat substrate layer **128** of FIG. **10**A and a patterned etch resist layer **129** having a surface relief diffractive topography. The surface relief diffractive topography is formed by patterning the etch resist layer **129**, e.g., using known semiconductor processing tools and techniques. For example, the etch resist layer can be patterned using any gray-scale lithography process such as, for example, techniques using a direct laser writing or exposure through a variable transmission high energy beam sensitive (HEBS) photo mask. The surface relief diffractive topography has a pattern of discontinuous diffractive structures. The surface relief diffractive topography can decrease in height at the periphery of the diffractive region to form a blend zone. The discontinuous diffractive structures may have a wide variety of shapes, e.g., such as those shown in FIGS. **8**A-**8**I. In one approach, the surface relief diffractive topography is formed by initially patterning the etch resist layer **127** with continuous diffractive structures and then cropping those structures to form discontinuous diffractive structures that have a smooth blending in height at their peripheral edge. Alternatively, the discontinuous diffractive structures and blend zones are patterned directly into the etch resist layer.

FIG. **10**C shows a side view of a lens **1002** having a patterned substrate layer **130** with the cropped diffractive optical power region **111** having the discontinuous diffractive structures **113** of FIG. **6**B. The discontinuous diffractive structures **113** are formed by transferring the surface relief diffractive pattern from the patterned etch resist layer **129** of FIG. **10**B to the flat substrate layer **128** of FIG. **10**B. In one approach, the pattern is transferred by placing the lens **1001** of FIG. **10**B into a dry-etch chamber such as, for example, a reactive ion etching (RIE) machine. The dry-etch chamber etches through both the patterned etch resist layer **129** and the flat substrate layer **128** of FIG. **10**B to transfer the diffractive pattern. Once transferred, the patterned substrate layer **130** of FIG. **10**C is formed having a blended cropped diffractive optical power region **111** with discontinuous diffractive structures **113**.

FIG. **11** is a graph of a measured surface topography of a mold for manufacturing a lens from the peripheral edge of the lens towards the center of the lens, in accordance with an aspect of the present invention. The lens has a cropped diffractive optical power region and a blend zone. The diffractive optical power region can be cropped, e.g., as described in FIGS. **7** and **9**B or alternatively, in FIGS. **10**A-**10**C. The cropped diffractive optical power region has a cropping boundary with an elliptical shape. The elliptical shape of the cropping boundary has a major axis of, e.g., approximately 30 mm and a minor axis of, e.g., approximately 16 mm. The blend zone includes diffractive structures having a continuous change in the heights that approach zero at the cropping boundary (i.e., where the peripheral edge of the diffractive optical power region meets the rest of the mold). The blend zone is positioned exterior to the cropping boundary. Alternatively, the blend zone is positioned interior to or centered at the cropping boundary. The blend zone has a width of, e.g., approximately 1 mm. Although, the blend zone can have a width in a range of, e.g., approximately 0.1 mm to approximately 5.0 mm, and preferably in a range of, e.g., approximately 0.2 mm to approximately 1.0 mm. The cropped diffractive optical power region provides, e.g., +1.25 diopters (D) of optical power for light having a wavelength of, e.g., 550 nanometers. Other dimensions, optical powers, and wavelengths can be used for the mold for casting a lens having other desired physical or optical properties.

The graph shows the height of the surface relief diffractive structures of the mold (measured in micrometers (μm)) along a length of the surface of the mold (measured in millimeters (mm)). The surface length in this example is measured along a measurement line **126** shown in FIG. **6**B. In this example, the measurements are provided by a Zygo white light interferometer.

FIGS. **12**A-**12**C are graphs of the surface topography, optical power, and diffractive efficiency of a lens, respectively, measured across a blend zone of a diffractive optical power region of the lens mold described in reference to FIG. **11**, in accordance with various aspects of the present invention.

The relationship between the diffractive efficiency in FIG. **12**C and the heights of the diffractive structures in FIG. **12**A measured along a length of the lens mold is defined by equations (2) and (3). As the heights of the diffractive structures decrease from a maximum value to zero, the diffractive efficiency of the blend zone likewise decreases to zero. The blend zone blends the diffractive region by varying the height of the diffractive structures and not the optical power thereof. As previously described, optical power is a function of the radii of the diffractive structures, e.g., according to equation (1), and is independent of the height of the diffractive structures. Thus, as the heights of the diffractive structures are varied for blending the diffractive efficiency, the optical power is not affected. Thus, a blended diffractive region having any optical power(s) can be achieved.

In FIG. **12**B, the optical power of the diffractive optical power region is constant. Light focused by a constant optical power region is focused to a single corresponding focal point. However, since the diffractive efficiency of the blend zone decreases to approximately zero at the peripheral edge of the region, the amount of light focused thereby (to the focal point) likewise decreases to zero. Thus, although there is an abrupt change in optical power across the peripheral edge of the diffractive optical power region, the amount of light focused by, and therefore the visibility of, the diffractive optical power region gradually approaches zero at the peripheral edge to form a lineless boundary.

FIG. **13**A is a graph of the surface topography of a lens having diffractive structures with an abrupt termination point **131** at a cropping boundary, in accordance with an aspect of the present invention. The graph shows the height, d, of the surface relief diffractive structures as a function of the radial distance, r, across the cropping boundary. The diffractive structures are concentric and have a series of crests and adjacent troughs forming a sawtooth pattern. Each concentric diffractive structure extends from a trough to a crest of the sawtooth pattern. Diffractive structures may be used described according to embodiments found in U.S. application Ser. No. 12/054,313 filed on Mar. 24, 2008 and entitled "Surface Relief Diffractive Optical Elements", which is incorporated herein by reference in its entirety.

FIG. **13**B is a graph of a blending function for blending the diffractive structures of the lens of FIG. **13**A for reducing the abrupt termination point at the cropping boundary, in accordance with an aspect of the present invention. The graph shows the blending function, m, as a function of the radial distance, r, across the cropping boundary. The blending function monotonically decreases from the center of the lens to the cropping boundary. The blending function is shown to be initially constant (e.g., having a value of 1 for not altering depth) and then gradually decreasing over a finite distance. The blending function can be any continuous function or mathematical relation, such as, for example, constant functions, linear functions, polynomial functions, trigonometric functions, exponential functions, hyperbolic functions, or logarithmic functions, either alone or in combination.

FIG. **13**C is a graph of the product, m*d, of the height, d, of the diffractive structures of FIG. **13**A and the blending function, m, of FIG. **13**B as a function of the radial distance, r, across the cropping boundary, in accordance with an aspect of the present invention.

FIG. **13**D is a graph of the blended surface topography of diffractive structures having heights that are the product of FIG. **13**C, in accordance with an aspect of the present invention. The graph shows the height, d, of the blended surface relief diffractive structures as a function of the radial distance, r, across the cropping boundary. The height of the blended surface relief diffractive structures is the product of the height of the non-blended surface relief diffractive structures and the blending function.

When the blending function is applied to the surface topography of the surface relief diffractive profile, the blending function causes a monotonic decrease of the diffractive efficiency over the width, w of the blending zone. For a diffractive optical power region having a plurality of concentric diffractive structures, the height of a first diffractive structure (i.e., the distance between a first crest and a first trough adjacent thereto) near the center point of the diffractive optical power region is greater than the height of a second diffractive structure (i.e., the distance between a second crest and a second trough adjacent thereto) spaced from the center point.

The product scales the heights of the diffractive structures by a value (n), e.g., between one and zero (at the cropping boundary). Scaling is the application of a value function by an operator. In the example of FIG. **13**C, the value function is a monotonically decreasing value function having a range of from 1 to 0 and the operator is multiplication.

By scaling the heights of the diffractive structures, the diffraction efficiency of the diffractive optical power region varies from a maximum to zero. The maximum diffraction efficiency occurs where the diffractive structures have full, unaltered peak heights. The maximum diffractive efficiency typically occurs near the center point of the concentric diffractive structures, i.e., interior to the blend zone. At the minimum (zero) diffraction efficiency, the diffractive optical power region focuses none of the incident light to the diffractive optical power. The minimum diffraction efficiency occurs where the diffractive structures have a peak height of zero. The minimum diffraction efficiency typically occurs at the periphery of the concentric diffractive structures, i.e., at the periphery of the blend zone.

At the region of maximum diffraction efficiency, the diffractive optical power region focuses approximately 100% of the incident light to the design optical power of the diffractive region. As the diffraction efficiency of the diffractive optical power region decreases to zero, the amount of light affected by the region decreases to zero and thus, the region becomes invisible. Thus, the lens having the blended surface topography of FIG. **13**D has a diffractive optical power region that is fully blended by varying the diffractive efficiency thereof.

FIG. **14**A is a graph of the surface topography of a lens having multi-level surface relief diffractive structures that end at an abrupt termination point **132** at a cropping boundary, in accordance with an aspect of the present invention. The surface topography of the multi-level surface relief diffractive structures is a discrete function, such as a stair-step function or a combination of square functions. The diffraction efficiency of the multi-level surface relief diffractive structure increases as the height of the highest level increases. Multi-level surface relief diffractive structures are known to approximate the surface relief diffractive structures of FIG. **13**A. The diffraction efficiency of a multi-level surface relief diffractive structure is less than the diffractive efficiency of the surface relief diffractive structures approximated thereby. As the number of levels per zone used to approximate the surface topography increases, the diffraction efficiency thereof likewise increases.

FIG. **14**B is a graph of a blending function for blending the surface topography of the diffractive structures FIG. **14**A for reducing the abrupt termination point at the cropping boundary, accordance with an aspect of the present invention. The blending function may be the blending function of FIG. **13**B.

FIG. **14**C is a graph of the product of the surface topography of the diffractive structures of FIG. **14**A and the blending function of FIG. **13**B, in accordance with an aspect of the present invention.

FIG. **14**D is a graph of the blended surface topography of diffractive structures having heights that are the product of FIG. **14**C, in accordance with an aspect of the present invention. As described in reference to FIGS. **13**A-**13**D, the lens having the blended surface topography of FIG. **13**D has a diffractive optical power region that is fully blended by varying the diffractive efficiency thereof.

Although a static diffractive optical element is described in the aforementioned figures having surface relief diffractive structures that utilize a physical gradation in surface topography predetermined to cause diffractive effects, alternatively, a dynamic diffractive optical element can be used, as shown in FIGS. **15**, **16**, and **17**A-**17**D to generate all of the optical results achieved by the static structure, in accordance with an aspect of the present invention.

FIG. **15** shows a first exploded cross-sectional view of an electro-active lens **200**, in accordance with an aspect of the present invention. The lens **200** includes an electro-active element **201** disposed between a first optical element **202** and a second optical element **203**. The electro-active element **201** includes a first substrate layer **204**, a second substrate layer **205**, transparent electrodes **207** and **208**, an insulating layer **209**, alignment layers **210** and **211**, and electro-active material **212**. A more detailed description of such embodiments may be found in U.S. application Ser. No. 12/018,048 filed on Jan. 22, 2008 and entitled "Cholesteric Liquid Crystalline Material", which is incorporated herein by reference in its entirety.

The electro-active element **201** is in optical communication with the first and second optical elements **202** and **203**. The electro-active element **201** is attached to the first and second optical elements **202** and **203**, e.g., by adhesive layers (not shown). The first and second optical elements **202** and **203** may be convex and concave, respectively, or otherwise shaped or finished to provide desired optical effects. For example, a refractive progressive optical power region can be formed on interior or exterior surfaces of a portion of either or both of the first and second optical elements to cause a progression in optical power. Either or both of the first and second optical elements **202** and **203** may have external surfaces which may be unfinished, semi-finished, or finished. Either or both optical elements **202** and **203** may be formed as the first and second substrate layers **204** and **205**, respectively.

The first substrate layer **204** has a flat surface topography and the second substrate layer **205** has a surface relief diffractive topography formed by diffractive structures **206**. Although the surface topography of the first substrate layer **204** is shown to be flat, any substantially featureless surface topography (e.g., curved) may be used. The transparent electrode **208**, alignment layer **211**, and the region containing the electro-active material **212**, are formed along the second substrate layer **205** and thus, also have a surface relief diffractive topography. Alternatively, the first substrate **204** also has a surface relief diffractive topography. As another alternative, the second substrate **205** has a flat surface topography and the first substrate **204** has a surface relief diffractive topography.

The first substrate layer **204** and the second substrate layer **205** may be coated with the transparent electrodes **207** and **208**, respectively. Transparent electrodes **207** and **208** may be uniformly deposited over the entire inner surfaces of the first substrate layer **204** and the second substrate layer **205**, respectively.

The electro-active material **212** may be contained between the first and second substrate layers **204** and **205**. The electro-active material **212** may be a liquid crystalline material, such as, a nematic liquid crystal, a cholesteric liquid crystal, a smectic liquid crystal, a polymer dispersed liquid crystal, or a polymer stabilized liquid crystal.

The alignment layers **210** and **211** align the molecules of the electro-active material **212** in a predetermined direction relative to the substrates layers **204** and **205**. The alignment layers **210** and **211** may be composed of, e.g., a polyimide material (for mechanical buffing), or a photosensitive material (for polarized UV optical alignment).

The transparent electrodes **207** and **208** may be electrically connected to a controller (not shown), e.g., via electrical contacts (not shown). The insulating layer **209** is disposed between the transparent electrodes **207** and **208** to prevent electric conduction (i.e., electrical shorting) between the transparent electrodes **207** and **208**. The controller applies voltages to the transparent electrodes **207** and **208** predetermined to cause an electric field to form across the electro-active material **212** as well as the alignment layers **210** and **211**. The electric field changes the orientation of the molecules of the electro-active material **212**, thereby changing the refractive index of the electro-active material **212**. The change in refractive index of the electro-active element **201** is predetermined to cause a diffractive pattern in the electro-active material **212** to provide optical power. When no voltage is applied to electrodes **207** and **208** the refractive index of the electro-active material **212** matches the refractive index of the surface relief diffractive structures **206**. Accordingly, no optical phase delay is generated and no light is focused (i.e. the diffraction efficiency is zero). When a predetermined voltage is applied to electrodes **207** and **208** the refractive index of the electro-active material **212** is different from the refractive index of the surface relief diffractive structures **206**. Accordingly, an optical phase delay is generated for focusing approximately all incident light to the optical power (i.e., approximately 100% diffraction efficiency). Thus, by switching the voltage applied to the transparent electrodes **207** and **208** on or off, the optical power of the electro-active element **201** is likewise switched on or off, thereby modulating the diffraction efficiency of the electro-active element **201** between a maximum and minimum values, respectively.

When voltage is applied to the electro-active element **201**, optical power is generated within a boundary **222**. The application of voltage causes an abrupt change in optical power across the boundary **222** formed by the outermost continuous surface relief diffractive structure(s). Thus, a visible line is formed in the lens **200**. To reduce the visibility of the line, a blend zone is needed.

The boundary **222** can be blended using a blend zone blending the heights of the diffractive structures **206** down to zero over a pre-determined distance at the boundary **222**. This blend zone is formed according to embodiments described in FIG. **9**A, **9**B, or **11**A-**11**C.

Although the electro-active element **201** in FIG. **15** is shown to be flat, it should be understood that the electro-active element **201** may alternatively be curved.

When the electro-active material is a polarization sensitive liquid crystalline material such as, e.g., a nematic liquid crystal, two electro-active elements are preferably used. The two electro-active elements are positioned in series and have alignment layers with orthogonal alignment directions to allow equal focusing of incident light of any polarization state. A more detailed description of such embodiments may be found in U.S. application Ser. No. 10/863,949 filed on Jun. 9, 2004 and entitled "Hybrid Electro-Active Lens", which is incorporated herein by reference in its entirety.

FIG. **16** shows a second exploded cross-sectional view of the electro-active lens **200** of FIG. **15** having an electro-active element **301** including the first substrate layer **204** and a second substrate layer **213**, both having a flat surface topography, in accordance with an aspect of the present invention. Although the surface topography of the first substrate layer **204** and the second substrate layer **213** are shown to be flat, any substantially featureless surface topography (e.g., curved) may alternatively be used.

The electro-active lens **300** has an electro-active element **301** that includes a patterned transparent electrode **214**, an alignment layer **215**, and a region containing the electro-active material **212**, each formed along the second substrate layer **213**. Since the second substrate layer **213** along which the aforementioned elements are formed, has a flat surface topography, these elements also have flat surface topographies.

The patterned transparent electrode **214** includes a plurality of individually addressable electrodes **216** (e.g., electrode rings or pixels). The individually addressable electrodes **216** are arranged for forming a diffractive optical power region in the lens **300**, as shown in FIGS. **17**A and **17**B. The transparent electrode **207** is a thin film transparent electrode layer that serves as a reference electrode an electrical ground) for the patterned transparent electrode **214**. When voltage is applied to the electro-active element **301** across the patterned transparent electrode **214** and the transparent electrode **207**, a diffractive pattern forms within a boundary **222** of the electro-active element **301**.

FIGS. **17**A and **17**B show front views of the patterned transparent electrode **214** of FIG. **16** having individually addressable electrodes **216** hound by the boundary **222**, in accordance with various aspects of the present invention.

The individually addressable electrodes **216** include a continuous full electrode **218**, a continuous closed curve electrode **219**, and a curved arc electrode **220**. Alternatively, the individually addressable electrodes **216** may only be discontinuous curve electrodes. The individually addressable electrodes **216** are shown to be shaped as circles or circular arcs, although other geometries such as elliptical or polygonal geometries may alternatively be used. Although 12 and 13 individually addressable electrodes **216** are shown in FIGS. **17**A and **17**B, respectively, any number of individually addressable electrodes **216** may be used. In a pixilated approach, any number and arrangement of pixels may be used. The individually addressable electrodes **216** are preferably concentric. The individually addressable electrodes **216** are optically transparent. The individually addressable electrodes **216** are composed of any of the known transparent conductive oxides (e.g., indium tin oxide (ITO)) or a conductive organic material (e.g., poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:TSS) or carbon nano-tubes).

The individually addressable electrodes **216** have individual electrical connections with a controller (not shown) along an electrical boundary **217**. An electrical insulating layer (not shown) is formed between the individually addressable electrodes **216**. The electrical insulating layer occupies spaces **221** firmed between adjacent individually addressable electrodes **216** to prevent electrical conduction therebetween.

The individually addressable electrodes **216** including at least one curved arc electrode **220** that can be positioned in any arrangement to form a diffractive optical power region having any shape. In FIG. **17**A the individually addressable electrodes **216** are arranged for generating an elliptically shaped diffractive optical power region, while in FIG. **17**B the individually addressable electrodes **216** are arranged for generating a flat-top segment shaped diffractive optical power region. Alternatively, the individually addressable electrodes **216** may be arranged and shaped differently for generating a diffractive optical power region having any shape (e.g., of FIGS. **8**A-**8**I).

When used in the lens **300** of FIG. **16**, voltages applied to the individually addressable electrodes **216** are predetermined to cause a voltage pattern across the electro-active material **212**. This voltage pattern, in turn, is predetermined to cause a change in the refractive index of the electro-active material **212** (and thus, the lens **300**). This change in refractive index forms a diffractive pattern and thus, a diffractive optical power region in the electro-active element **301**.

FIG. **18**A shows a side view of a radially peripheral portion of the electro-active lens **300** of FIG. **16** having a plurality of individually addressable electrodes **216**, in accordance with an aspect of the present invention.

FIG. **18**B shows voltages applied to the individually addressable electrodes **216** predetermined to cause a diffractive optical power region in the electro-active element **301** of FIG. **16**, in accordance with an aspect of the present invention. The voltages (e.g., four voltages; V**1**, V**2**, V**3**, and V**4**) are applied to the individually addressable electrodes **216**. The voltages are applied in a repeating sequence of monotonically increasing voltages to the individually addressable electrodes **216** in the order that the individually addressable electrodes **216** are radially arranged. The voltages form a multi-level voltage pattern across the electro-active material **212** predetermined to cause a multi-level diffractive pattern in the electro-active element **301**. The multi-level diffractive pattern of FIG. **18**B is similar to the multi-level surface relief diffractive pattern of FIG. **14**A. However, the multi-level diffractive pattern of FIG. **18**B is formed by a variation in refractive index, while the multi-level surface relief diffractive pattern of FIG. **14**A is physically formed by a variation in the heights of diffractive structures. Diffractive structures may refer to any structures capable of diffracting light. In one example, diffractive structures may refer to surface relief diffractive structures having a physically formed sawtooth pattern including a series of crests and adjacent troughs, as shown in FIGS. **13**A, **13**D, **14**A, and **14**D. In another example, in FIG. **15**, diffractive structures may refer to the diffractive structures **206** having the sawtooth pattern, the electrode **208** having the sawtooth pattern, or a combination thereof and/or other components of electro-active element **201**. In yet another example, in FIG. **16**, diffractive structures may refer to the individually addressable electrodes **216** having a uniform or flat surface topography. In this example, the diffraction of light is formed by applying a voltage pattern for varying the refractive index of the electro-active material **212**.

In this example, although the diffractive structures (i.e., the individually addressable electrodes **216**) are capable of diffracting light, when no voltage is applied thereto, the diffractive structures do not diffract light.

When the voltage of FIG. **18**B are applied to the individually addressable electrodes **216** of FIG. **18**A, a diffractive pattern in the electro-active element **301** forms within the boundary **222** causing an abrupt change in optical power across the boundary **222** causing a visible line in the lens. To solve this problem, a blend zone is needed.

In the aforementioned figures a static blend zone is described, which utilizes a physical variation in the heights of the diffractive structures to cause a blending of diffractive efficiency to reduce a visibility of a line at the boundary **222** of a diffractive structure. However, since the lens **300** of FIG. **16** utilizes the patterned transparent electrode **214** that has a flat surface topography, an alternative blending means is needed.

FIG. **18**C shows voltages applied to the individually addressable electrodes **216** predetermined to cause a blending of the diffractive optical power region in the electro-active element **301** of FIG. **16**. A blending function (e.g., of FIGS. **13**B-**13**D and **14**B-**14**D) modulates the profile by monotonically decreasing the diffractive efficiency from the radial center of the lens **300** to the boundary **222** over a finite distance. The blending function scales the voltage amplitudes applied to the individually addressable electrodes **216** by a value (m), e.g., between 1 and 0 (at the boundary **222**). As the voltage amplitudes applied to the individually addressable electrodes **216** approach zero near the boundary **222**, the change in refractive index in the lens **300** and thus the diffractive effects caused thereby (i.e., diffraction efficiency) also approach zero near the boundary **222**. As the diffraction efficiency of the lens **300** decreases to zero, the boundary **222** becomes invisible.

Although four voltages are shown in FIGS. **18**B and **18**C, any number of voltages can be used. The larger the number of distinct voltages (and thus levels per Fresnel zone or voltage period), the better the approximation to an ideal diffractive structure. However, the width of one period of the sequence of voltages, and thus, the width of the individually addressable electrodes **216** to which these voltages are applied, determines the diffractive optical power of the lens **300**. In order to preserve this diffractive optical power, as the number of distinct voltages used to approximate a diffractive structure is increased, the number of individually addressable electrodes **216** in the same region must likewise be increased. Thus, the density of individually addressable electrodes **216** is increased. To fit more individually addressable electrodes **216** into the same sized region of the lens **300**, the individually addressable electrodes **216** can be narrowed and moved closer together. When the spacing between the individually addressable electrodes **216** is reduced, the potential for electrical conduction (i.e., Shorting) between adjacent individually addressable electrodes **216** is increased. Accordingly, additional insulation (not shown) may be used between the individually addressable electrodes **216** to prevent such electrical conduction.

The dynamic blending means of FIG. **18**A is not a physical structure, but an electrical state, e.g., of voltages predetermined to cause the blending of diffractive efficiency. The blending means is preferably integral to the electro-active element **301**.

In another approach, the voltage amplitudes are not modulated by the blending function. In this approach, the voltage amplitudes are not decreased at the source (the individually addressable electrodes) but instead are intercepted by insulating material (not shown) placed near the periphery of the electro-active element. The insulating material has a monotonically increasing thickness predetermined to reduce the voltage amplitudes according to the voltage pattern shown in FIG. **18**C. Thus, the effect of blending the diffractive efficiency of the diffractive optical power region is the same yet caused by the predetermined placement of insulating material instead of modulating the applied voltage.

Any of the aforementioned means for blending the diffraction efficiency of the diffractive optical power region may be used in conjunction with conventional optical power blend zones (e.g., taught in Stewart et. al., U.S. application Ser. No. 11/595,871, which is incorporated herein by reference in its entirety). When used together in a lens, the diffraction efficiency blend zone and the optical power blend zone may be separately disposed or alternatively, may partially or fully overlap.

In FIG. **18**A, the electro-active lens **300** includes a spacer **223** for controlling the thickness of the electro-active material **212**.

FIG. **19**A shows a front view of a progressive addition diffractive optical power region **133**, in accordance with an aspect of the present invention. The progressive addition diffractive optical power region has a plurality of concentric surface relief diffractive structures for focusing light of a specific wavelength λ to a focal length f. The progressive addition diffractive optical power region **133** is static or dynamic. The progressive addition diffractive optical power region **133** has a first region that includes the concentric surface relief diffractive structures **110** with radii from the center point, r, in a first range, $d_2<r\leq d_1+d_2$. The progressive addition diffractive optical power region **133** has a second region that includes the concentric surface relief diffractive structures **110** with radii from the center point, r, in a second range, $r\leq d_1$. For example, the second region is positioned radially interior to the first region.

The progressive addition diffractive optical power region **133** has a progression of optical power as the radial distance thereof increases from the center point. In the figure, the optical power of the progressive addition diffractive optical power region **133** is constant in the second region. To achieve the constant optical power, the radius of the n^{th} concentric surface relief diffractive structure **110** of the second region from the center point thereof is equal to $\sqrt{2n\lambda f}$ (i.e., according to the definition of equation (1)). In the figure, the optical power of the progressive addition diffractive optical power region **133** decreases in the first region as the radial distance from the center point thereof increases. To achieve the decreasing optical power progression, the radii of at least some of the diffractive structures **110** deviate from the definition of equation (1). To achieve a progression of decreasing optical power, the radius of the n^{th} concentric surface relief diffractive structure of the first region from the center point thereof is greater than $\sqrt{2n\lambda f}$. Alternatively, the optical power of the progressive addition diffractive optical power region **133** increases in the first region as the radial distance from the center point thereof increases. To achieve a progression of increasing optical power, the radius of the n^{th} concentric surface relief diffractive structure of the first region from the center point thereof is less than $\sqrt{2n\lambda f}$. In one example, the radial widths of at least some of the diffractive structures are equal to one another, e.g., in the first region.

The optical power progression of the progressive addition diffractive optical power region **133** is shown in a graph **134**. In the figure, the optical powers of the progressive addition diffractive optical power region **133** decrease with increasing radial distance. Accordingly, the relative radial widths of the diffractive structures of the progressive addition diffractive optical power region **133** decreases at a slower rate than in a constant diffractive optical power region. Since the degree of chromatic aberration decreases as the width of the diffractive structures increase, the chromatic aberration of the progressive addition diffractive optical power region **133** is less than the chromatic aberration of a constant diffractive optical power region. It is experimentally observed that a progressive addition diffractive optical power region providing +1.00 D of optical power and composed of typical spectacle lens materials exhibits a degree of chromatic aberration below a predetermined threshold level (e.g., a noticeable level) at radial distances less than 6 mm from the center of the progressive addition diffractive optical power region **133**.

If the degree of chromatic aberration, e.g., of a +1.00 D progressive addition diffractive optical power region **133** at 6.0 mm from the center thereof is below a predetermined threshold level, then so too are other regions having diffractive structures having the same radial width, e.g., a +0.50 D diffractive optical power region at 12.0 mm from the center, a +0.33 D diffractive optical power region at 1.8.0 mm from the center and a +2.00 D diffractive optical power region at 3.0 mm from the center. The radial widths of the diffractive structures, which determines the chromatic aberration thereof, is locally constant at each radial distance and decreases with increasing radius. This approach forms a progressive addition diffractive optical power region **133** having uniform chromatic aberration for all diffractive structures. The progressive addition diffractive optical power region **133** can be cropped at a cropping boundary to remove diffractive structures predetermined to cause chromatic aberration greater than a predetermined threshold.

FIGS. **19**B and **19**C show front views of the progressive addition diffractive optical power region **133** of FIG. **19**A being cropped along the cropping boundary **116**, in accordance with various aspects of the present invention. FIG. **19**B shows a cropped progressive addition diffractive optical power region **135** with a wider than tall near distance vision zone and an optical power progression in both the vertical and horizontal directions. FIG. **19**C shows a cropped progressive addition diffractive optical power region **135** with a narrower than tall intermediate to near distance vision zone and an optical power progression in only or mostly the vertical direction. It may be appreciated that the progressive addition diffractive optical power region **135** can be cropped to have any desired shape (e.g., as shown in FIGS. **8**A-**8**I).

A diffractive efficiency blend zone can blend the cropped progressive addition diffractive optical power region **135** of FIGS. **19**B and **19**C by reducing the diffractive efficiency thereof to zero radially extending towards the peripheral edge thereof. Since the diffractive efficiency blend zone blends independently of optical power, the blend zone can blend the cropped diffractive optical power region along the entire cropping boundary thereof (having varying optical power) to reduce the appearance of a line along the cropping boundary **116**.

The progressive addition diffractive optical power regions of FIGS. **19**A-**19**C may have different optical power progressions in the vertical and horizontal directions. Additionally, the optical power progressions need not terminate to a zero optical power.

FIG. **20**A shows the cropped progressive addition diffractive optical power region **135** of FIG. **19**B with an optical power progression along a vertical axis **140** and an optical power progression along a horizontal axis **141**, in accordance with an aspect of the present invention.

FIGS. **20**B, **20**C and **20**D show graphs of the optical power along axes **140** and **141** of FIG. **20**A, in accordance with various aspects of the present invention.

In FIGS. **20**B and **20**C, the optical power progression **143** is the optical power along the vertical axis **140** of FIG. **20**A and the optical power progression **145** is the optical power along the horizontal axis **141** of FIG. **20**A. In FIGS. **20**B and **20**C, the constant optical power **142** is the optical power along both the vertical and horizontal axes **140** and **141** of FIG. **20**A, where the optical powers coincide. The optical powers typically coincide in the near distance vision region.

In FIG. **20**B, the optical power progression **143** along the vertical axis decreases monotonically to approximately a zero optical power **144** (i.e., plano) outside of the near distance vision region. The optical power progression **145** along the horizontal axis decreases monotonically to the non-zero optical power **146** outside of the near distance vision region. In one example, the optical power along the horizontal axis decreases to the non-zero optical power **146** that is in a range of from approximately 50% to approximately 75% of the constant optical power **142**, although other non-zero optical powers may be used.

In FIG. **20**C, both the optical power progression **143** along the vertical axis and the optical power progression **145** along the horizontal axis decrease monotonically to non-zero optical powers **148** and **146**, respectively, outside of the near distance vision region. In one example, the optical power along the vertical axis decreases to the non-zero optical power **148** that is in a range of from approximately +0.12 D to approximately +1.00 D, but is preferably in a range of from approximately +0.25 D to approximately +0.75 D, although other non-zero optical powers may be used.

When the optical power progression **143** along the vertical axis decreases to a non-zero optical power **148** (in an intermediate distance vision region), there is a discontinuity in the optical power between the far-intermediate and intermediate distance vision regions. These discontinuities typically cause undesirable optical effects, such as, image breaks or a step-up in optical power, when viewed across the distance and intermediate distance vision regions. The degree of an image break typically depends on the magnitude of the change in optical power at the discontinuity.

In FIG. **20**D the optical power along the vertical axis is the constant optical power **142** in the near distance vision region and a discrete monotonic decreasing optical power **149** (e.g., as a stair-step or piecewise function) to either a zero optical power **150** or a non-zero optical power **151**. The discontinuities in the discrete optical power progression can be blended with an optical power blend zone or diffraction efficiency blend zone.

Alternatively, the optical power of the cropped progressive addition diffractive optical power region **135** of FIG. **19**B may vary radially according to any mathematical function, e.g., such as, constant functions, linear functions, polynomial functions, trigonometric functions, exponential functions, hyperbolic functions, logarithmic functions, or any combination thereof. The diffractive optical power variation in a spectacle lens may occur over distances in a range of from approximately 6 mm to approximately 16 mm, or from approximately 8 mm to approximately 14 mm, and preferably from approximately 10 mm to approximately 12 mm.

FIGS. **21**A and **21**B show front views of lenses **400** having the cropped progressive addition diffractive optical power regions **135** of FIG. **19**B having astigmatism less than a predetermined threshold and providing a wearer's full near distance vision prescription, in accordance with an aspect of the present invention. Since the cropped progressive addition diffractive optical power region **135** provides the wearer's full near distance vision prescription, no additional optics are required.

In FIG. **21**A, the progressive addition diffractive optical power region **135** provides a continuous monotonically increasing progression of optical power ranging from a minimum optical power region **158** (e.g., a plano region) having zero optical power to a maximum optical power region **159** (e.g., a region having +1.25 D of optical power).

In FIG. **21**B, the progression of optical power may vary from a non-zero minimum optical power region **160** to a maximum optical power region **159** (e.g., a region having +1.00 D of optical power). The optical power progression of FIG. **21**B (e.g., that terminates at the non-zero minimum optical power region) is typically not considered a progressive addition lens (PAL), which is generally defined to have an optical power progression that terminates to zero optical power. When the wearer's full near distance vision prescription is, e.g., +1.50 D or less of optical power in the near distance vision region (e.g., for emerging presbyopes) correction may be fully provided by cropped the progressive addition diffractive optical power region **135**.

In some cases, removing the diffractive structures by cropping the cropped progressive addition diffractive optical power regions **135** decreases the optical power of the lens **400** to be less than the optical power prescribed to a wearer. In other cases, e.g., when the wearer's full near distance vision prescription is greater than +1.50 D, the cropped the progressive addition diffractive optical power region **135** providing the greater than +1.50 D optical power, does not provide sufficient reduction in chromatic aberration and unwanted astigmatism. In such cases, the cropped progressive addition diffractive optical power region (e.g., providing a portion of the optical power needed) may be combined with a refractive optic, such as, a refractive progressive addition region (e.g. providing a portion of the optical power needed), to provide the full optical power needed.

FIGS. **22**A-**22**B show front views of the lenses **400** of FIGS. **21**A-**21**B having the cropped progressive addition diffractive optical power regions **135** of FIG. **19**B in optical communication with the refractive progressive addition region **103** of FIG. **1**, in accordance with an aspect of the present invention. The cropped progressive addition diffractive optical power region **135** has astigmatism less than a predetermined threshold and has less than a wearer's full near distance prescription. The refractive progressive addition region **103** provides the remainder of the optical power needed to provide the wearer's full near distance vision prescription. In one example, the wearer's full near distance vision prescription is, e.g., +2.00 D of optical power in the near distance vision region. For example, +1.00 D of optical power is provided by the progressive addition diffractive optical power region **135** and +1.00 D of optical power is provided by the refractive progressive addition region **103**.

In FIG. **22**A, the progressive addition diffractive optical power region **135** and the refractive progressive addition region **103** each have a minimum optical power region **158** with zero optical power (e.g., a plano region). The minimum optical power region is located where the peripheral edges of the regions meet the top of the progressive channel. Thus, there is no step-up in optical power at the top of the progressive channel. In FIG. **22**B, the progressive addition diffractive optical power region **135** begin at a non-zero (e.g., +0.25 D) minimum optical power region **160**. Thus, there is a (e.g., +0.25 D) step-up in optical power at the top of the progressive channel.

FIGS. **23**A and **23**B are contour plots of the optical power and astigmatism, respectively, of the refractive progressive addition region of FIG. **1**. In the figure, the refractive progressive addition lens provides a maximum (+2.00 D in this example) of optical power in a near distance vision region **136**.

The refractive progressive addition region has a compromised vision region that causes incident light to experience astigmatism greater than a predetermined threshold. Astigmatism greater than the predetermined threshold is located in region(s) **137** of the astigmatism contour plot. Since astigmatism greater than 1.00 D generally causes noticeable distortion and swim when viewed in a lens, the predetermined threshold value may be approximately 1.00 D, and is preferably 0.25 D, although other values may be used. In FIG. **23**B, there are two of the regions **137** on respective sides of the progressive channel, although there may be any number and position(s) of the regions **137**. In this example, the regions **137** have a maximum astigmatism of approximately 2.00 D.

To reduce the unwanted astigmatism of the regions **137**, the cropped progressive addition diffractive optical power region **135** of FIG. **19**B can be used to approximate the refractive progressive addition region of FIG. **1**, while having the cropping boundary **116** that excludes the compromised vision region that causes the unwanted astigmatism of the regions **137**.

FIGS. **23**C and **23**D are contour plots of the optical power and astigmatism, respectively, of the cropped progressive addition diffractive optical power region **135** of FIG. **19**B approximating the +2.00 D optical power progression in the near distance vision region of the refractive progressive addition region of FIG. **1**.

The unwanted astigmatism (e.g., up to MOD) in the regions **137** of the refractive progressive addition lens shown in FIG. **23**B, is greater than the unwanted astigmatism (e.g., up to 1.25 D) in region **138** of the cropped progressive addition diffractive optical power region shown in FIG. **231**) for the same optical powers **136** and **139**, respectively. Thus, using the cropped progressive addition diffractive optical power region to provide a portion or all of the needed optical power can reduce the astigmatism compared with using the refractive progressive addition region alone. It may be appreciated that cropping the diffractive optical power region may reduce but not eliminate astigmatism. For example, FIG. **23**D shows cropping can reduce astigmatism to be below the predetermined threshold value of astigmatism, e.g., less than 1.00 D and preferably, less than 0.25 D.

FIGS. **24**A and **24**B are contour plots of the optical power and astigmatism, respectively, of the progressive addition diffractive optical power region **133** of FIG. **19**A. FIGS. **24**A and **24**B include an optical power region **161** (e.g., of up to +1.00 D of optical power) and an astigmatism region **163** having astigmatism less than or equal to the predetermined threshold value (e.g., 0.25 D), respectively, in accordance with various aspects of the present invention.

FIGS. **24**C and **24**D are contour plots of the optical power and astigmatism, respectively, of the cropped progressive addition diffractive optical power region **135** of FIG. **19**A, respectively. FIGS. **24**C and **24**D include cropped areas of greater than the predetermined threshold value (e.g., 0.25 D) of astigmatism **165**, in accordance with various aspects of the present invention. Other optical powers and threshold values may be used.

FIGS. **24**E and **24**F are contour plots of the optical power and astigmatism, respectively, of the lens **400** of FIG. **22**A, which includes the cropped progressive addition diffractive optical power region **135** of FIG. **19**B and the refractive progressive addition region **103** of FIG. **1**, in accordance with various aspects of the present invention. The optical power of the lens will be the addition of the optical power region **161** of the cropped progressive addition diffractive optical power region and an optical power region **162** of the refractive progressive addition region. In this example, the optical power region **161** provides a first progression of optical power (e.g., of up to +1.00 D) and the optical power region **162** provides a second progression of optical power (e.g., of up to +1.00 D) for providing the lens with a combined optical power progression (e.g., of up to +2.00 D) in the near distance vision region **136**. Likewise, the astigmatism of the lens will be the addition of the astigmatism region **163** having astigmatism less than or equal to the predetermined threshold value of astigmatism **165** (e.g., 0.25 D) and an astigmatism region **164** including astigmatism of the refractive progressive addition region. In this example, the astigmatism region **163** provides astigmatism equal to the predetermined threshold value of astigmatism (e.g., of up to 0.25 D) and the astigmatism region **164** provides astigmatism (e.g., of up to 1.00 D) associated with the (e.g., +1.00 D optical power) of the refractive progressive addition region. Thus, the lens will have a total of up to 1.251) of astigmatism. The 1.25 D of astigmatism formed by combining the cropped progressive addition diffractive optical power region and the refractive progressive addition region to provide +2.00 D of optical power is less than the 2.00 D of astigmatism formed by the refractive progressive addition region providing the +2.00 D of optical power alone (as shown in FIG. **23**B).

In one example, when the wearer's full, near distance vision prescription is, e.g., +1.00 D or less, and preferably +0.75 D or less, of optical power in the near distance vision region (e.g., for emerging presbyopes with some accommodation remaining), correction may be fully provided by a diffractive optical power region having constant optical power.

FIGS. **25**A-**25**D show front views of the lenses **400** of FIGS. **21**A-**21**B having the cropped diffractive optical power regions **111** of FIGS. **8**G, **8**E, **8**I, and **6**B, respectively, with constant optical power, in accordance with various aspects of the present invention. The cropped diffractive optical power regions **111** of FIGS. **25**A-**25**D have a variety of shapes, although it may be appreciated that any portion of a continuous diffractive optical power region can be cropped. The cropped diffractive optical power regions **111** can be static as shown in FIGS. **8**A-**8**I or dynamic, formed by the transparent electrode **208** coating the surface relief diffractive structures **206** as shown in FIG. **15**, or by the individually addressable electrodes **216**, as shown in FIGS. **17**A-**17**B.

FIGS. **26**A-**26**D show front views of the lenses **400** of FIGS. **25**A-**25**D having the cropped diffractive optical power region **111** with constant optical power in optical communication with the refractive progressive addition region **103** of FIG. **1**, in accordance with various aspects of the present invention.

The refractive progressive addition region **103** may be spaced from the cropping boundary **116** of the cropped diffractive optical power region **111**. For example, the refractive progressive addition region **103** may begin below the optical power discontinuity of the cropping boundary **116**, e.g., spaced by a distance in a range of from approximately 0 to approximately 6 mm (measured along the vertical axis).

In one example, the wearer's near distance vision prescription is, e.g., approximately +2.00 D; far-intermediate distance vision prescription is, e.g., approximately +0.62 D; and intermediate distance vision prescription is, e.g., approximately +1.00 D. To provide the total optical power for the prescriptions in this example, the lens **400** of FIG. **26**B may have the cropped diffractive optical power region **111** providing a constant optical power, e.g., of up to +0.62 D. The cropped diffractive optical power region **111** may have a largest diffractive structure having a diameter of approximately 40 mm. The lens **400** may have the refractive progressive addition region **103** begin approximately 6 mm below the optical power discontinuity of the cropping boundary **116** having approximately zero (piano) optical power. The refractive progressive addition region **103** may increase optical power to provide +0.38 D at a distance of 9 mm from the optical power discontinuity of the cropping boundary **116** (e.g., in the intermediate distance vision region). The +0.38 D of optical power contributed by the refractive progressive addition region **103** is combined in the lens **400** with the +0.62 D of optical power contributed by the cropped diffractive optical power region **111** to provide a total of +1.00 D of optical power for the intermediate distance vision prescription of the wearer. The refractive progressive addition region **103** provides up to +138 D of optical power, which when combined with the +0.62 D provided by of the cropped diffractive optical power region **111**, provides a total of +2.00 D near distance vision prescription of the wearer. The portion of the cropped diffractive optical power region **111** that is situated above the refractive progressive addition region **103** provides correction of the wearer's far-intermediate distance vision prescription. In another example, the optical power needed to correct for near distance vision may be split equally between the cropped diffractive optical power region **111** and the refractive progressive addition region **103**. In this example, if the wearer's near distance vision prescription is +2.50 D, the cropped diffractive optical power region **111** provides +1.25 D of constant optical power and the refractive progressive addition region **103** provides a progression of up to +1.25 D of optical power.

In FIGS. **26**A-**26**D, since the refractive progressive addition region **103** is spaced from the cropping boundary **116** of the cropped diffractive optical power region **111**, the shape and size of the refractive progressive addition region **103** depends upon the shape and size of the cropped diffractive optical power regions **111**.

FIGS. **27**A-**27**D show front views of the lenses **400** of FIGS. **26**A-**26**D having the refractive progressive addition region **103** located at least partially outside of the cropping boundary **116** of the cropped diffractive optical power region **111**, in accordance with various aspects of the present invention. For example, the refractive progressive addition region **103** may begin above the optical power discontinuity of the cropped diffractive optical power region **111**, e.g., by a distance in a range of from approximately 0 to approximately 6 mm (measured along the vertical axis).

In one example, the wearer's near distance vision prescription is, e.g., approximately +2.50 D; far-intermediate distance vision prescription is, e.g., approximately +0.75 D; and intermediate distance vision prescription is, e.g., approximately +1.25 D. To provide the optical power for the prescriptions in this example, the lens **400** of FIG. **26**B may have the diffractive optical power region **111** providing a constant optical power, e.g., of up to +0.75 D. The refractive progressive addition region **103** may have approximately zero (i.e., plano) optical power at a distance of 3 mm above the optical power discontinuity of the cropping boundary **116**. The refractive progressive addition region **103** may increase optical power to provide +025 D of optical power at the optical power discontinuity to reduce step-up at the discontinuity. The refractive progressive addition region **103** may increase optical power to approximately +0.50 D of optical power at a distance of 6 mm below the optical power discontinuity (e.g., in the intermediate distance vision region). The +0.50 D of optical power contributed by the refractive progressive addition region **103** is combined in the lens **400** with the +0.75 D of optical power contributed by the cropped diffractive optical power region **111** to provide a total of +1.25 D of optical power for the intermediate distance vision prescription of the wearer. The refractive progressive addition region **103** provides up to +1.75 D of optical power, which when combined with the +0.75 D provided by the cropped diffractive optical power region **111**, provides the total +2.50 D near distance vision prescription of the wearer.

In FIGS. **27**A-**27**D, since the refractive progressive addition region **103** is located above the optical power discontinuity of the cropping boundary **116**, the shape and size of the refractive progressive addition region **103** depends upon the shape and size of the cropped diffractive optical power regions **111**.

In other embodiments, the refractive progressive addition region or the cropped diffractive optical power region may be used alone for correcting a high (e.g., greater than +1.00 D) near distance vision prescription for a wearer. Alternatively, the refractive progressive addition region or diffractive optical power region may be used in combination for correcting a low (e.g., less than +1.00 D) near distance vision prescription for a wearer to further reduce distortion and chromatic aberration typically associated with a purely refractive or diffractive lens.

The lenses **400** of FIGS. **19**A-**19**C, **20**A-**20**D, **21**A-**21**B, **22**A-**22**B, **25**A-**25**D, **26**A-**26**D, and **27**A-**27**D can be static or dynamic, in accordance with various aspects of the present invention.

FIGS. **28**A-**28**B show side views of the static lens **100** of FIGS. **3** and **4**, in accordance with various aspects of the present invention. The lens **100** has a first layer **152** including diffractive structures **110** having a surface relief diffractive topography (forming a diffractive optical power region).

In FIG. **28**A, the diffractive structures **110** are formed on the first layer **152**. The first layer **152** is composed of a first material with a first refractive index (n_1). The first layer **152** is in optical communication with a second layer **153** composed of a second material with a second and different refractive index (n_2). The height d of the diffractive structures **110** are preferably defined as follows:

$$d(n_1-n_2)=d(\Delta n)=\lambda \tag{4}$$

Where λ is the design wavelength of the diffractive optical power region. As the difference in refractive index, Δn, increases, the heights of the diffractive structures **110** decrease. Diffractive structures **110** that are shorter are easier to manufacture and less visible. However, increasing the difference in refractive index generally increases interfacial Fresnel reflections between the first and second materials, which decrease the transmission of light through a final finished lens. Accordingly, the difference in refractive index Δn is, e.g., in a range of from approximately 0.02 to approximately 0.25, and is preferably in a range of from approximately 0.05 to approximately 0.15. Additionally, the transmission of light across the two materials or any optical material interface may be increased by using thin film, quarter-wave, and index matching layers, which are known in the art.

In one approach, in accordance with an aspect of the present invention, the lens **100** is manufactured by initially generating a pre-form of the first layer **152** or second layer **153** having the surface relief diffractive structures **110**. The pre-form is then joined with the remaining portion of the lens **100**, e.g., using optical quality adhesive. The pre-form may be manufactured, e.g., by casting a thermal or ultra-violet (UV) cure monomer resin. Alternatively, the pre-form may be manufactured by injection molding, embossing, stamping or otherwise thermo-forming a thermoplastic material, as is known in the art. The pre-form may act as a consumable mold. When a pre-form of the second layer **153** is firmed, an inner surface of the pre-form has the diffractive structures **110** and an outer surface of the pre-form (forming the front surface of the lens **100**) can be formed as a refractive optic, e.g., such as a progressive addition region. The progressive addition region is preferably aligned in a predetermined orientation with respect to the surface relief diffractive structures to ensure that the far, far-intermediate, and intermediate to near distance vision regions are properly generated. The thickness of the pre-form and any material added to the pre-form are such that the surface relief diffractive structures **110** are spaced approximately 1 mm or less from the finished front surface of a final lens.

As described above, the refractive indices of the first layer **152** and the second layer **153** must be different. In one example, one of the first layer **152** and the second layer **153** is composed of MR-20 (having a refractive index of 1.594) while the other is composed of Trivex (having a refractive index of 1.53). In one example, one of the first layer **152** and the second layer **153** is composed of CR39 (having a refractive index of 1.49) while the other is composed of TS216 (having a refractive index of 1.59). In yet another example, one of the first layer **152** and the second layer **153** is composed of MR-10 (having a refractive index of 1.668) while the other is composed of Trivex (having a refractive index of 1.53).

In general, the lenses **100** may be composed of any of the materials listed in Table 1, although other material may be used.

TABLE 1

Material	Refractive Index	Abbe Number	Supplier
CR39	1.49	55	PPG
Nouryset 200	1.49	55	Great Lakes
Rav-7	1.50	58	Great Lakes
Trivex	1.53	44	PPG
Brite-5	1.548	38	Doosan
Brite-Super	1.553	42	Doosan
TS216	1.59	32	Tokuyama
Polycarbonate	1.59	30	Multiple
MR-20	1.594	43	Mitsui
MR-8	1.597	41	Mitsui
Brite-60	1.60	35	Doosan
UDEL P-1700 NT-06	1.634	23.3	Solvay
Radel A-300 NT	1.653	22	Solvay
MR-7	1.665	31	Mitsui
MR-10	1.668	31	Mitsui
Radel R-5000 NT	1.675	18.7	Solvay
Eyry	1.70	36	Hoya
Essilor High Index	1.74	33	Essilor

FIG. **28**B shows the lens **100** of FIG. **28**A having a third layer **154** composed of a third material having a third refractive index (n_3). If the third layer **154** is a pre-form, then diffractive structures **110** are formed on the third layer **154**. The third layer **154** is disposed between the first substrate layer **152** and the second substrate layer **153**. The refractive index of the third layer **154** is different from the refractive index of one or both of the first layer **152** and the second layer **153**. The refractive indices of the first layer **152** and the second layer **153** can be the same or different. The third refractive index is, e.g., in a range of from approximately 1.50

to approximately 1.75 and the first and second refractive indices are, e.g., in a range of from approximately 1.40 to approximately 1.65. In this example, material having a relatively high refractive index is surrounded by material having a relatively low refractive index. Alternatively, the third refractive index is, e.g., in a range of from approximately 1.40 to approximately 1.65 and the first and second refractive indices are, e.g., in a range of from approximately 1.50 to approximately 1.75. In this example, material having a relatively low refractive index is surrounded by material having a relatively high refractive index. Such an arrangement typically generates thinner and flatter finished lenses as compared with the opposite configuration (for lenses having the same optical power).

The first layer **152** and the second layer **153** of FIG. **28**B may be manufactured using pre-forms with surface relief diffractive structures, as described in reference to FIG. **28**A. The third layer **154** may take the form of an optical quality adhesive used to adhere the first substrate layer **152** to the second substrate layer **153**. The optical quality adhesive has optical properties, e.g., to enable the height of the surface relief diffractive structures **110** to satisfy equation (4) (i.e., to have high diffraction efficiency). The thickness of the third layer **154** (including the diffractive structures) is, e.g., in a range of from approximately 0.05 mm to approximately 1.00 mm, and is preferably in a range of from approximately 0.1 mm to approximately 0.5 mm.

Alternatively, the third layer **154** may be manufactured as a surface relief diffractive pre-form (e.g., insert). The first layer **152** and the second layer **153** may subsequently be joined to the pre-form using an embedding casting process similar to that used to manufacture polarized sun lenses; which is well known in the art.

As described above, the refractive index of the third layer **154** is different from the refractive indices of one or both of the first layer **152** and the second layer **153**. In one example, one or both of the first layer **152** and the second layer **153** are composed of MR-20 while the third layer **154** is composed of Trivex. In another example, one or both of the first layer **152** and the second layer **153** are composed of CR39 while the third layer **154** is composed of TS216. In yet another example, one or both of the first layer **152** and the second layer **153** are composed of MR-10 while the third layer **154** is composed of Trivex. Alternatively other materials, e.g., listed in Table 1 may be used.

FIG. **28**C shows the lens **100** of FIG. **28**B having optical quality adhesive layers **155** disposed on either side of the third substrate layer **154** for joining with the first layer **152** and the second layer **153**. The first, second, and third layers **152**, **153**, and **154**, may be formed as a pre-form and then joined by optical quality adhesive layers **155**. The thickness of the optical quality adhesive layers **155** is, e.g., in a range of from approximately 0.05 mm to approximately 1.00 mm and is preferably in a range of from approximately 0.1 mm to approximately 0.5 mm.

FIG. **28**D shows the lens **100** of FIG. **28**B having the third layer **154** encapsulated within a material **156** to form a material insensitive insert **157**. The material insensitive insert **157** is disposed between the first layer **152** and the second layer **153**. The material insensitive insert **157** may be joined to the first layer **152** and the second layer **153** using an optical quality adhesive. Alternatively, the material insensitive insert **157** may be embedded between the first layer **152** and the second layer **153**, e.g., using a casting process similar to that used to manufacture polarized sun lenses, which is well known in the art. The material insensitive insert **157** fully contains the diffractive structures **110**. Thus, according to equation (4), the diffraction efficiency of the lens **100** depends on the refractive index difference between the third layer **154** and the material **156** and is independent of (i.e., insensitive to) the refractive indices of the layers **152** and **153**. Accordingly, the first layer **152** and the second layer **153** may be composed of any variety of optical materials and the material insensitive insert **157** will generate optical power with the same diffraction efficiency. By offering a variety of material(s) for the first substrate layer **152** and the second substrate layer **153** and generally the same materials for the material insensitive insert **157**, a variety designs of lens **100** may be achieved with a reduced number of manufacturing SKUs and production tooling, as compared to the aforementioned approaches of FIGS. **28**A-**28**C.

In another embodiment of the invention (not shown), a layer of a photo-sensitive material with uniform thickness (i.e., no surface relief diffractive structures) is placed between two pre-formed optical components. The refractive index of the photo-sensitive material permanently and irreversibly changes to a predetermined value when exposed to optical radiation. The photo-sensitive material may be exposed to radiation in a pattern predetermined to form the diffractive optical power region. For example, the diffractive phase profile may be "written" on the photo-sensitive material by means of exposure through an optical mask or a scanning laser source. The optical radiation is, e.g., within the ultra-violet or visible wavelength bands, although other wavelengths can be used.

Although the lenses **100** shown in FIGS. **28**A-**28**D are semi-finished blanks (SFB), other lenses and finishes may be used, such as, finished lenses, finished lens blanks, or unfinished lens blanks. Although the first substrate layer **152** is shown in FIG. **28**A-**28**D to be unfinished, the back surface of the first substrate layer **152** is typically ground and polished or free-formed to generate a patient's distance vision prescription using methods known in the art. It is understood that the lenses **100** shown in FIGS. **28**A-**28**D can be edged to fit in a spectacle lens frame as well as drilled to be mounted to a rimless spectacle lens frame.

In another embodiment of the invention (not shown), the lens can further include static tints or dynamic tints (by adding a photochromic), anti-reflection coatings, anti-soiling coatings, scratch resistance hard coatings, ultra-violet absorbing coatings, and coatings for selective filtering of high energy light.

It may be appreciated that the diffractive structures described in accordance with the present invention do not change the total amount of light traversing the lens, i.e., they do not block light, such as by polarization or tinting. Instead, the diffractive structures affect the portion of the total amount of light focused to a focal point of the diffractive optical power region. When the diffractive optical power region is used in combination with a refractive host lens, the remaining portion that is not focused to the focal point of the combination of the diffractive optical power region and the refractive host lens is focused to the focal point of the refractive host lens.

What is claimed is:

1. A lens system comprising:

a diffractive optical power region comprising a plurality of concentric diffractive structures, wherein a greater fraction of light incident on a diffractive structure near the center point of the concentric diffractive structures contributes to the optical power of the diffractive optical power region than light incident on a diffractive structure peripherally spaced therefrom, wherein the diffractive optical power region is cropped so as to include at least one discontinuous diffractive structure and at least one diffractive structure with a complete closed curve.

2. The lens system of claim **1**, wherein the plurality of concentric diffractive structures comprise a series of crests and adjacent troughs forming a sawtooth pattern, wherein each concentric diffractive structure extends from a trough to an adjacent crest of the sawtooth pattern, wherein the distance between a crest and an adjacent trough of the diffractive structure near the center point is greater than the distance between a crest and an adjacent trough of the diffractive structure peripherally spaced therefrom.

3. The lens system of claim **2**, further comprising:

a first electrode layer formed along the sawtooth pattern;

electro-active material formed along the first electrode layer;

a second electrode layer formed along the electro-active material and electrically connected to the first electrode layer;

a controller for applying voltage across the first and second electrode layers; and

wherein when the controller applies voltage across the first and second electrode layers, the refractive index of electro-active material is altered to provide the optical power of the diffractive optical power region and wherein the difference in the fraction of light which contributes to the optical power of the diffractive optical power region is due to the difference in the height of the diffractive structure near the center point and the height of the diffractive structure spaced therefrom.

4. The lens system of claim **1**, wherein the concentric diffractive structures comprise individually addressable electrodes and the diffractive optical power region comprises:

a controller for applying voltages to a plurality of the individually addressable electrodes; and

electro-active material disposed between the individually addressable electrodes, wherein when the controller applies voltages to the plurality of individually addressable electrodes, the refractive index of the electroactive material is altered to provide the optical power of the diffractive optical power region and wherein the difference in the fraction of light which contributes to the optical power of the diffractive optical power region is due to a difference in the refractive index of the electro-active material between adjacent individually addressable electrodes of the diffractive structure near the center point and the refractive index of the electro-active material between adjacent individually addressable electrodes of the diffractive structure spaced therefrom.

5. The lens system of claim **4**, wherein the individually addressable electrodes include concentric curved electrodes.

6. The lens system of claim **4**, wherein the individually addressable electrodes include pixels.

7. The lens system of claim **1**, wherein the fraction contributed to the optical power monotonically decreases as the radial distance of the diffractive structure increases from the center point.

8. The lens system of claim **7**, wherein the fraction contributed to the optical power is constant within a first radial distance and decreases within a second greater radial distance.

9. The lens system of claim **1**, wherein the fraction is approximately zero at the peripheral edge of the diffractive optical power region.

10. The lens system of claim **1**, wherein the fraction is approximated by a piecewise function.

11. The lens system of claim **1**, wherein the optical power is constant.

12. The lens system of claim **1**, wherein the optical power is progressive.

13. The lens system of claim **1**, wherein the at least one diffractive structure with the complete closed curve forms a circle or an ellipse.

14. The lens system of claim **1**, wherein the complete closed curve is located radially interior to the at least one discontinuous diffractive structure.

15. The lens system of claim **1**,

the diffractive optical power region has a peripheral edge, wherein the diffractive optical power region focuses light to a focal point, wherein the amount of light focused on the focal point from the center point is greater than the amount of light focused on the focal point from the peripheral edge.

16. The lens system of claim **15**, wherein the amount of light focused on the focal point monotonically decreases as the distance increases from the center point.

17. The lens system of claim **15**, wherein the amount of light focused on the focal point is scaled by a function having a range of from zero to one.

18. The lens system of claim **15**, wherein the amount of light focused on the focal point is approximately zero at the peripheral edge of the diffractive optical power region.

19. The lens system of claim **15**, wherein the amount of light focused on the focal point is nonzero at the peripheral edge of the diffractive optical power region.

20. The lens system of claim **15**, wherein the lens system is static.

21. The lens system of claim **15**, wherein the lens system is dynamic.

22. The lens system of claim **21**, wherein the plurality of concentric diffractive structures are surface relief structures and have a series of crests and adjacent troughs forming a sawtooth pattern, wherein each concentric diffractive structure extends from a trough to an adjacent crest of the sawtooth pattern, wherein the distance between a first crest and a first adjacent trough near the center point is greater than the distance between a second crest and a second adjacent trough spaced from the center point, wherein: the diffractive optical power region includes a first region comprising a plurality of the concentric diffractive structures for focusing light of a specific wavelength A to a focal length f, wherein the radius of the n^{th} concentric diffractive structure of the first region from the center point is greater than $\sqrt{2n\lambda f}$; and

wherein the lens system is electro-active.

23. The lens system of claim **15**,

wherein a first region comprises the plurality of concentric diffractive structures that are surface relief structures and focus light of a specific wavelength λ to a focal length f, wherein the radius of the n^{th} concentric diffractive structure from the center point is greater than $\sqrt{2n\lambda f}$.

24. The lens system of claim **23**, wherein the diffractive optical power region provides a progression of decreasing optical power.

25. The lens system of claim **23**, wherein the diffractive optical power region further comprises a second region having a plurality of concentric diffractive structures that are surface relief structures, wherein the radius of the n^{th} concentric diffractive structure of the second region from the center point thereof is approximately equal to $\sqrt{2n\lambda f}$.

26. The lens system of claim **25**, wherein the second region provides a constant optical power.

27. The lens system of claim **25**, wherein the second region is positioned radially interior to the first region.

28. The lens system of claim **23**, wherein the radial widths of at least some of the diffractive structures of the first region are equal to one another.

29. The lens system of claim **15**,

wherein a first region comprises a plurality of concentric diffractive structures that are surface relief structures and focus light of a specific wavelength λ to a focal length f, wherein the radius of the n^{th} concentric diffractive structure from the center point is less than $\sqrt{2n\lambda f}$.

30. The lens system of claim **29**, wherein the radial widths of at least some of the diffractive structures of the first region are equal to one another.

31. The lens system of claim **29**, wherein the diffractive optical power region provides a progression of increasing optical power.

32. The lens system of claim **29**, wherein the diffractive optical power region further comprises a second region having a plurality of concentric diffractive structures that are surface relief structures, wherein the radius of the n^{th} concentric diffractive structure of the second region from the center point thereof is approximately equal to $\sqrt{2n\lambda f}$.

33. The lens system of claim **32**, wherein the second region provides a constant optical power.

34. The lens system of claim **32**, wherein the second region is positioned radially interior to the first region.

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